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Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments

Soil and Material Engineers, Inc., Cary, NC

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Gregory N. Richardson
Robert M. Koerner

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Soil & Material Engineers, Inc.
Cary, North Carolina 27511

Geosynthetic Research Institute
Drexel Univ., Philadelphia, PA 19014

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16. ABSTRACT

This report provides guidance design procedures for the use of geosynthetic materials in hazardous waste land disposal cells. Primary geosynthetic components include flexible membrane liners (FML) used to limit the flow of leachate, and leachate collection and removal systems (LCR) used to monitor for leakage and to remove leachate from the system. Also presented is design guidance for ancillary components including ramps, interior berms, and standpipes. A design procedure is developed for each of the potential failure modes, based on calculation of field service conditions. A Design Ratio (DR) is then calculated as the ratio of the limiting performance of the component, based on laboratory tests, to the actual performance calculated for field conditions. Minimum Design Ratios are recommended for each design procedure. Guidelines are also presented for evaluating the long-term stability of each component. Factors that influence stability are rhelogical properties, aging characteristics, growth of microorganisms, and deformations due to settlement. Chemical compatibility is not considered in this document.

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by

Gregory N. Richardson
Soil & Material Engineers, Inc.
Cary, North Carolina 27511

Robert M. Koerner
Geosynthethic Research Institute
Drexel University
Philadelphia, Penn. 19014

Contract No. 68-03-3338

Project Officer:
Robert Hartley
Land Pollution Control Division
Hazardous Waste Engineering Research Laboratory
Cincinnati, OH 45268

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OH 45268

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report provides design information for the use of geosynthetic materials in hazardous waste containment systems, such as landfills and surface impoundments. Information is included on geomembranes for liquid containment and liquid repellence, and on geofabrics used for subsurface liquid drainage. The report is intended to fill a need in standardizing and improving containment system designs.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

Abstract

Geosynthetic Design Guidance
For
Hazardous Waste Landfill Cells and Surface Impoundments

This report focuses on the development of guidance design procedures for the evaluation of geosynthetic materials used in hazardous waste land disposal cells and surface impoundments. These procedures are demonstrated in typical applications. Primary geosynthetic components include flexible membrane liners (FML) used to limit the flow of leachate, and leachate collection/removal systems (LCR) that monitor for potential leakage of an FML and provide for removal of the leachate from the system. Also presented is design guidance for ancillary components including ramps, interior berms, and standpipes. The ancillary components are generally controlled by operational and not statute criteria. Chemical compatibility of the geosynthetic components and leachate is not considered in this guidance document.

Potential failure modes for each geosynthetic component are established. A design procedure is developed for evaluating each of the potential failure modes. Each design procedure is based on calculation of service conditions in the component under field conditions. A Design Ratio (DR) is then calculated as the ratio of the limiting performance of the component based on laboratory tests to the actual performance calculated for field conditions. Minimum values for Design Ratio are recommended for each design procedure.

Specific geosynthetic material properties are required to determine the DR in each design procedure. A suggested range of values, based on available data, is presented for each material property used. Additionally, a summary of the test procedures used in evaluating each specific material property is provided in the manual. Relevant standards for each test are referenced when available.

Long-term performance of each component is dependent on the stability of each material property over the design life of the facility. Time-dependent factors that can influence components include material rheological properties, material aging characteristics, growth of micro-organisms within the system, and deformations due to settlement of the contained waste. Guidelines for evaluating the long-term stability of each component are presented.

The appendices of the report include a Glossary of terms and a summary of the major design and index tests commonly used in Geosynthetic applications.

TABLE of CONTENTS

Page
Foreword iii
Abstract iv
Tables vii
Figures viii
Design Examples ix

Section I Introduction and Background
  Scope of Document I-1
  Geomembranes I-1
  Geotextiles I-3
  Geogrids/Geonets. I-4
  Goecomposites. I-4
  Secure Landfills. I-5
  Surface Impoundments I-9
  Long-term Considerations I-10
  Summary. I-10

Section II Summary
  Design Priorities II-3
  Research Needs II-4

Section III Design of Components Beneath Cell
  Component Functions III-1
  Leachate Collection/Removal(LCR) Systems. III-2
    Transmissivity Criteria III-2
    Filter Criteria III-6
    Strength Criteria III-9
    Primary vs Secondary LCR Systems III-10
  Flexible Membrane Liners (FML) III-10
    FML Vapor Transmission. III-11
    FML Stresses III-12
    FML Seaming III-15
    FML Survivability III-17
    FML Anchorage. III-21
  Surface Impoundment Considerations. III-25
    FML Protection III-25
    Gas Venting III-27

Section IV Design of Components Within Cell
  Ramp and Traffic Considerations. IV-1
  Interior Berms IV-4
  Standpipe for Primary LCR IV-5
    Down-Drag Forces. IV-6
    FML Strain Due to Down-Drag Forces. IV-7
  Monitor for Secondary LCR. IV-8

Section V Design of Components Above Cell
  Surface Water Collection/Removal (SWCR) V-5
    SWCR Transmissivity V-5

SWCR Filtration V-6
SWCR Strength V-7
Flexible Membrane Cap (FMC) V-7
FMC Permeability. V-8
FMC Stresses V-9
FMC Seaming V-10
FMC Survivability During Installation. V-11
Biotic Barrier V-12
Gas Collection and Venting V-12
Vapor Transmissivity V-15
Vent Pipe Details V-16

Section VI Construction/Fabrication Considerations

Flexible Membrane Liners/Caps VI-2
Specifications VI-2
Fabrication VI-6
Construction VI-8
Construction Quality Assurance VI-17
Drainage/Filtration Components VI-25
Specifications VI-25
Construction VI-28
Construction Quality Assurance VI-28
Subgrade VI-29
Specifications VI-30
Construction VI-30
Construction Quality Assurance VI-31

Section VII Long-term Service Considerations

Flexible Membrane Liners VII-1
Chemical Attack VII-1
Photochemical Attack VII-2
Ozone Attack VII-2
Biological (Micro-organisms) Attack VII-3
Thermal Effects VII-5
Environmental Stress Cracking VII-6
Environmental Stress Rupture. VII-7
Aging Effects from Soil Burial VII-8
Leachate Collection/Removal Systems VII-10
Creep/Stress Relaxation Effects. VII-10
Chemical Attack VII-10
Biological (Micro-organisms) Attack VII-13
Thermal Effects VII-14
Aging Effects from Soil Burial VII-15
Cell Cap Performance VII-15
Hydrolysis Effects VII-15
Gas Venting and Interaction VII-17
Special Concerns. VII-17

Section VIII Appendices

Conversion of Units. A-1
Glossary B-1
Index Test Procedures C-1
Design Test Procedures. D-1
INDEX E-1

List of Tables

Page

Table 1.1 Basic Composition of Polymeric Geomembranes I-3

Table 2.1 Design Priorities - Liner System II-3
Table 2.2 Design Priorities - Cap System II-4

Table 3.1 Tear Resistance of FML III-20

Table 6.1 Available NDT Methods for Evaluating Seams VI-6
Table 6.2 Wind Uplift Forces VI-14
Table 6.3 Overview of Nondestructive Geomembrane Seam Tests . . VI-22

Table 7.1 Micro-Biological Attack on Plastics VII-4
Table 7.2 Thermal Properties of FMLs VII-5
Table 7.3 Burning Characteristics of FML Polymeric Materials . VII-6
Table 7.4 Soil Burial Tests on Polyester VII-9
Table 7.5 Chemical Resistance Properties of Fibers VII-12
Table 7.6 Alkalinity Study on Geotextiles VII-13
Table 7.7 Biological Effects on Geotextile Strength VII-14
Table 7.8 Effects of Heat on Fiber Properties VII-16
Table 7.9 Results of Soil Burial Tests VII-17
Table 7.10 Moisture Regain and Water Imbimition of Fibers . . .VII-19

LIST OF FIGURES

Page

Figure 1.1 Synthetic/Clay Double Liner System I-5
Figure 1.2 Synthetic/Composite Double Liner System I-6
Figure 1.3 Composite/Composite Double Liner System I-7
Figure 1.4 Proposed RCRA Cell Cap Profile I-9

Figure 2.1 Growth in American Geosynthetic Market II-2

Figure 3.1 Profile of MTG Double Liner System III-1
Figure 3.2 Leachate Head vs Collector Pipe Spacing III-3
Figure 3.3 Elastic Compression Curves-Transmissivity III-5
Figure 3.4 Settlement Trough Models III-13
Figure 3.5 Compressive Stress Model III-14
Figure 3.6 Configuration of Geomembrane Field Seams III-15
Figure 3.7 Seam Strength Tests III-17
Figure 3.8 Puncture and Impact Resistance III-19
Figure 3.9 FML Anchors - Details III-22
Figure 3.10 Forces and Variables - Anchor Analysis. III-24
Figure 3.11 Liner Cover Stability Analysis III-27
Figure 3.12 Gas Vent - Details III-29

Figure 4.1 Geometry of Typical Ramp IV-1
Figure 4.2 Cross-Section of Typical Access Ramp IV-2
Figure 4.3 Interior Berm - Waste Separation IV-4
Figure 4.4 Interior Berm - Operations IV-5
Figure 4.5 Standpipe/Drain - Details IV-6
Figure 4.6 Isolated Standpipe - Details IV-7
Figure 4.7 Standpipe Induced Strain in FML IV-9
Figure 4.8 Sidewall Standpipe - Detail IV-10
Figure 4.9 Standpipes for Secondary LCR System IV-11

Figure 5.1 Geosynthetics in RCRA Double FML Cell Profile V-4
Figure 5.2 Transmissivity Data for Geotextile V-6
Figure 5.3 FML Stress-Strain Performance V-10
Figure 5.4 Seaming Composite Membrane V-11
Figure 5.5 Water Trap in Vapor Collector system V-14
Figure 5.6 Air and Water Transmissivity in Geotextile V-15
Figure 5.7 Gas Vent Pipes - Details V-16

Figure 6.1 Panel - Seam Identification Scheme VI-7
Figure 6.2 Design Maximum Wind Speed VI-14
Figure 6.3 FML Anchorage to Concrete - Details VI-16
Figure 6.4 Rigid/Flexible Penetrations - Details VI-18
Figure 6.5 Panel Placement Log VI-23
Figure 6.6 Geomembrane Seam Test Log VI-23
Figure 6.7 Geomembrane Repair Log VI-24

Figure 7.1 Laboratory Environmental Stress Cracking/Rupture . . VII-7
Figure 7.2 Influence of pH on Permittivity of Geotextile . . .VII-11
Figure 7.3 Strength Behavior of Nylon and Polyester in Water . .VII-18
Figure 7.4 Phases of Solid Waste Decomposition VII-18
Figure 7.5 "Sky Mound" Cap Planned for Hackensack Meadowland . .VII-21

LIST OF EXAMPLES

Example 3.1 LCR - Transmissivity:Waste Criteria. III-32
Example 3.2 LCR - Transmissivity:Surface Water Criteria . . . III-33
Example 3.3 LCR - Transmissivity:Creep III-34
Example 3.4 LCR - Permitivity III-35
Example 3.5 LCR - Filter:Retention III-36
Example 3.6 LCR - Filter:Clogging III-37
Example 3.7 LCR - Strength:Sliding III-38
Example 3.8 LCR - Settlement:Limit Analysis III-39
Example 3.9 LCR - Settlement:Strain Compatibility III-40
Example 3.10 LCR - Transmissivity:Response Time III-41
Example 3.11 LCR - Strength:Composite Primary Liner. III-42
Example 3.12 FML - Permeability via WVT III-43
Example 3.13 FML - *De Minimis* Psuedo Permeability III-44
Example 3.14 FML - Tensile Stress:Liner Weight III-45
Example 3.15 FML - Tensile Stress:Down Drag at Filling. . . . III-46
Example 3.17 FML - Localized Subsidence III-47
Example 3.18 FML - Anchor Trench III-48
Example 3.19 Soil Cover - Stability III-49

Example 4.1 Ramp - Sliding Stability IV-13
Example 4.2 Ramp - Hydraulic Capacity IV-14
Example 4.3 Ramp - Wheel Loading on FML IV-15
Example 4.4 Standpipe - Down-Drag Forces IV-16
Example 4.5 Standpipe - Puncture Failure of FML. IV-17

Example 5.1 SWCR - Transmissivity V-19
Example 5.2 Cover Soil - Stability / SWCR - Shear Strength . . V-20
Example 5.3 SWCR - Tensile Failure V-21
Example 5.4 FMC - Settlement V-22

Example 6.1 Wind Uplift - FML Placement VI-34

SECTION I

INTRODUCTION AND BACKGROUND

SCOPE OF DOCUMENT

This design guidance document was prepared to provide recommendations for the design of synthetic components within hazardous waste land disposal cells and surface impoundments. The synthetic components include flexible membrane liners, textiles, nets, grids and composites. All these synthetic components that are used within the ground are commonly called geosynthetics. The 'geo' prefix indicates the usage of the component on or in the earth and is commonly applied to individual synthetic components. Thus, synthetic flexible membrane liners used within the ground are called geomembranes, etc. Both the application of geosynthetic materials to civil engineering functions and the design of secure hazardous waste landfills are emerging technologies with little cross-over expertise existing at present. A majority of the references on geosynthetics are less than five years old, and the current secure landfill configurations date from the November 1984 Hazardous and Solid Waste Amendments (HSWA). While providing guidance to facility designers and regulators, this document may spur manufacturers of geosynthetic components into developing components designed specifically for hazardous waste facilities. A Glossary of terms generic to geosynthetics is provided in the appendix because they are not commonly available.

Geosynthetic components incorporated in the design of hazardous waste facilities provide certain hydraulic functions as follows:

(1) Geomembranes limit the movement of leachate in the system,

(2) Geotextiles act as a filter to prevent the flow of soil fines into drainage systems, or to provide planar flow for drainage, or as a cushion to protect geomembranes,and

(3) Geonets and nonwoven geotextiles allow planar flow of liquids and serve as drainage systems.

Recently, composite materials have been developed to serve multiple hydraulic functions. In addition to hydraulic functions, geosynthetic composites can act as tensile elements to reinforce tensile-weak soils and to bridge cracks caused by differential settlement of the waste fill material.

GEOMEMBRANES

Geomembranes are impermeable synthetic liners used to control fluid migration. Moisture moves through the membranes as a diffusion process driven by concentration gradients (Fick's first Law) and not as a fluid flow (Darcy's Law). These materials have an equivalent Darcian permeability of typically 10^{-14} to 10^{-13} cm/s. In general applications, geomembranes are made of compounds having a base product of asphalt and/or polymer. Only polymer-based geomembranes are reviewed in this document. Polymers used to make geomembranes are synthetic chemical compounds of high molecular weight. The most common polymers used in making geomembranes are linear or slightly branched molecular structures that are thermoplastic. Thermoplastics undergo no chemical changes when repeatedly softened by heating and solidified again by cooling.

The most common types of polymers used in the manufacture of geomembranes are as follows (Giroud and Frobel, 1984):

Thermoplastics; Polyvinyl chloride (PVC), oil resistant PVC (PVC-OR), thermoplastic nitrile-PVC (TN-PVC), ethylene interpolymer alloy, polyethylene (PE), elasticized polyolefin.

Crystalline Thermoplastics; Low density polyethylene (LDPE), linear-low density polyethylene (LLDPE), high density polyethylene (HDPE), high density polyethylene-alloy (HDPE-A), polypropylene, elasticized polyolefin.

Thermoplastic Elastomers; Chlorinated polyethylene (CPE), chlorinated polyethylene -alloy (CPE-A), chlorosulfonated polyethylene (CSPE), thermoplastic ethylene -propylene diene monomer (T-EPDM).

Elastomers; Isoprene-isobutylene rubber (butyl rubber), ethylene-propylene diene monomer (EPDM), polychloroprene (CR) (neoprene), epichlorohydrin rubber (CV).

Note that the symbols in parentheses are those adopted by the National Sanitation Foundation (NSF 54) and are common market abbreviations. Currently the predominant geomembrane liner materials in industrial and hazardous waste applications are HDPE, PVC, and CSPE (Waugh,1983,1984).

It should be noted that the common usage of the term High Density polyethylene (HDPE) does not agree with its more formal definition under ASTM D-1248 (Polyethylene Plastics Molding and Extrusion Materials). Under this standard, polyethylenes are classified as follows:

Type	Nominal Density, gm/cm^3
I	.910 to .925
II	.926 to .940
III	.941 to .959
IV	.960 and higher

Type III is classified as high density polyethylene but reflects a higher density than most commercial "HDPE" materials. The Type II materials are classified as linear medium-density polyethylene but are commercially referred to as "HDPE". This document uses the more common usage of "HDPE" and thus will usually be referring to these Type II materials.

Additives are typically compounded with polymers to improve the physical or long-term aging characteristics of the geomembrane. Processing aids may be added to reinforce or soften the compound during the manufacturing process. Plasticizers are commonly used to impart flexibility to a normally rigid polymer. Protection from ultraviolet light

Table 1.1 Basic Composition of Polymeric Geomembranes
(after Haxo, 1986)

Component	Composition of compound type (parts by weight)		
	Crosslinked	Thermoplastic	Semicrystalline
Polymer or alloy	100	100	100
Oil or plasticizer	5-40	5-55	0-10
Fillers:			
Carbon Black	5-40	5-40	2-5
Inorganics	5-40	5-40	---
Antidegradants	1-2	1-2	1
Crosslinking system:			
Inorganic system	5-9	---	---
Sulfur system	5-9	---	---

(UV) aging is provided by adding carbon black to the base polymer. In light colored membranes, UV protection is achieved by the addition of titanium dioxide. Additional aging protection may be provided by the use of antioxidants to reduce the effect of surface oxidation and ozone, and fungicides that prevent fungi and bacteria from attacking the polymer. The percentage of a given membrane that is composed of such additives is surprisingly high as shown in Table 1.1 (Haxo, 1986). The high percentage of additives such as plasticizers makes it imperative that a 'fingerprint' of the components of a given liner be known so that it can be verified that the same polymer used to meet chemical compatibility requirements is installed in the field.

Most geomembranes are manufactured using an extrusion, calendering, or spread-coating process. The HDPE membranes gaining usage in hazardous waste facilities are manufactured by extrusion of the polymer into a non-reinforced sheet. Calendering forms a membrane by passing a heated polymeric compound through a series of heated rollers. Spread coating produces a reinforced membrane by coating a fabric with the polymer. Reinforced membranes can also be produced using the extrusion or calendering processes if the reinforcing fabric is laminated to the membrane while the polymer is still hot.

GEOTEXTILES

Geotextiles are fabrics constructed of fibers of synthetic materials and intended for engineering applications within soils. Each geotextile may be classified as to the type of polymer, fiber, and fabric style used in its construction. A majority of geotextiles in use today are manufactured from polypropylene or polyester materials. The polypropylenes offer greater chemical resistance while the polyesters exhibit less creep under constant loads. Fiber types include continuous monofilament or monofilament yarns, short lengths of fibers called staple, yarns made from staple fibers, and fibers formed by slitting sheets of polymer. The fabric styles include woven, nonwoven, and knit construction.

Geotextiles are relatively high permeability materials developed to allow the movement of liquid through the geotextile while at the same time preventing the movement of adjacent soil particles. Additionally, geotextiles can be used as a reinforcement to provide tensile strength to soils and to bridge discontinuities that may develop in the subgrade. Nonwoven fabrics are generally used to play a hydraulic role in a design system, while woven and knit fabrics are used primarily in reinforcement roles. Nonwoven fabrics play a large role in the design of hazardous waste systems because the design emphasis is on control of leachate flow and prevention of erosion.

Nonwoven geotextiles are generally manufactured in a four step process: fiber preparation, web formation, web bonding, and post-treatment. Fiber preparation includes concurrent formation of continuous filaments by extrusion of molten polymer through a spinneret nozzel, or advanced formation of staples for later processing. Web formation produces a uniform layer of unbonded fibers either by direct spraying of continous filaments or the use of cards, garnetts, or air laying of staples on a moving conveyor belt. Web bonding interlocks the individual fibers and is commonly achieved using a melt-bonding, resin-bonding, or needle-punched process. Post-treatment of the nonwoven geotextile may include impregnating it with (1) an acrylic resin to improve abrasion resistance, or (2) a fungicide to limit growth of fungi and bacteria in the fabric. Polymers generally used to make geotextiles include polypropylene, polyester, and most recently polyethylene.

GEOGRIDS and GEONETS

Geogrids and geonets are relatively new products even for geosynthetics. These materials are based on extruded polypropylene or polyethylene. Grids are formed by first punching a regular pattern of holes into sheeting and then drawing the sheeting uniaxially or biaxially. The drawing process increases the modulus and strength of the sheeting. Geogrids are principally used as reinforcement materials but can provide limited planar flow capacity. Geonets are extruded nets formed by extruding and bonding of up to three layers of polymer rods oriented at acute angles to each other. While lacking the high strength of the oriented geogrids, the geonets provide a significant capacity for planar flow and are commonly used to form leachate or surface water collection/removal systems.

GEOCOMPOSITES

Geocomposites are high drainage polymeric systems made of a built-up drainage core covered with a geotextile that acts as a filter. The cores consist of columns, ribs, extruded nubs, etc., and vary widely in size, shape, strength, and flow capacity. They are made from polystyrene, PE, PVC, or other polymers. The geotextile is usually attached to the core by heat bonding, thermal glues, or with conventional adhesives. Care must be taken to insure that the adhesive used does not contain sufficient volatile organics that it contributes to the leachate. There are currently a large number of geocomposites commercially available with typical applications including being used as a substitute for lateral drains in roadways and as back-of-wall drainage for retaining walls.

SECURE LANDFILLS

On November 8, 1984, the Resource Conservation and Recovery Act (RCRA) was amended by the Hazardous and Solid Waste Amendments (HSWA). Among the provisions that went into effect were minimum technological requirements for hazardous waste land disposal facilities, Section 3004(o). HSWA requires that new units and lateral expansions of existing units at hazardous waste landfills and surface impoundments must have two or more liners and a leachate collection system above (for landfills) and between such liners. Additionally, HSWA required that new units and lateral expansions of existing units at interim status waste piles (those in existence on November 19, 1980) must meet the existing standards for liners and leachate collection as contained in 40CFR264.251. A minimum "double" liner composed of a single flexible membrane (FML) overlying a 3-foot thick clay liner was allowed under HSWA pending issuance of EPA regulations or guidance documents.

EPA draft Minimum Technology Guidance (MTG) Documents for liners and leachate collection systems were made available on December 20, 1984 and on May 24, 1985. Proposed codification of statutory provisions based on these minimum technology guidance documents is outlined in the Federal Register, Vol. 51, No. 60, March 28, 1986. In the draft guidance and proposed codification, EPA defines performance requirements for two designs that it feels meet minimum technological requirements for hazardous waste landfills and surface impoundments.

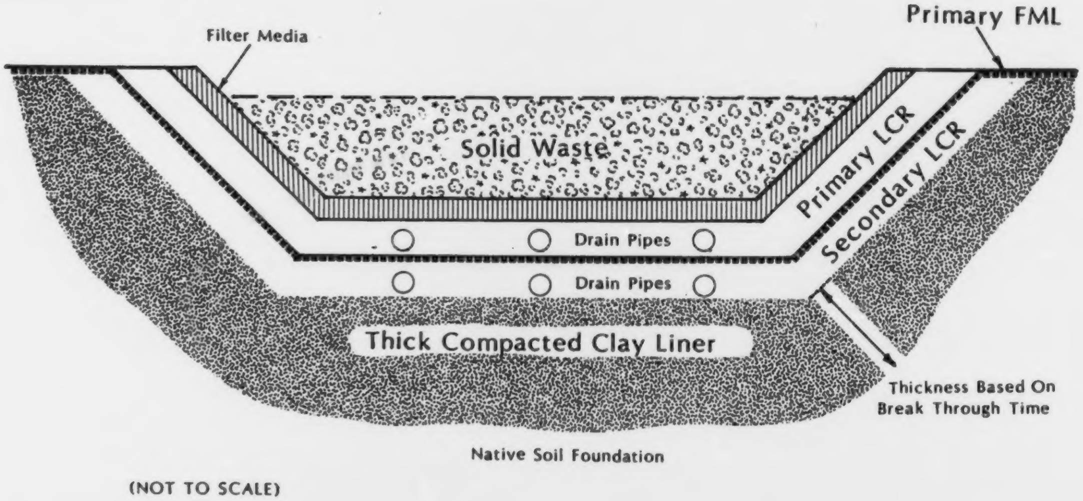

Figure 1.1 Synthetic/Clay Double Liner System (EPA, 1985a)

The first "double-liner" system in the proposed codification is a synthetic liner/clay liner design as shown in Figure 1.1. This design includes a top synthetic liner designed and constructed of materials to minimize the migration of any leachate constituents into the liner during the "active" life of the facility and the minimum 30 year "postclosure care period." The lower clay liner is designed to limit the migration of any constituent through the liner during this same period. The thickness of the clay liner is a function of design, with a minimum thickness of 3 feet specified. The actual thickness of the clay liner is controlled by the calculated breakthrough time for a single constituent of the leachate to pass through the clay liner. A conservative design assumes that the interior FML will be penetrated the first year in service and will therefore use a minimum 30-year breakthrough design.

Within the first system, the leachate collection and removal system between the two liners must be able to rapidly detect and collect all liquids leaking through the top liner, withstand chemical attack from the leachate, and provide continuous service throughout the postclosure care period.

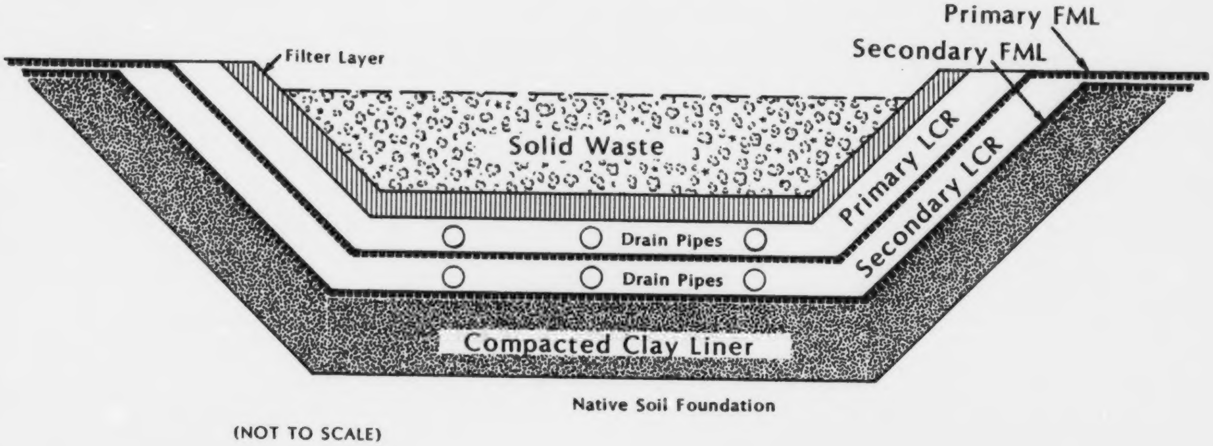

Figure 1.2 Synthetic/Composite Double Liner System (EPA, 1985a)

The second "double-liner" design is shown on Figure 1.2 and includes a synthetic top liner and a composite bottom liner. At a minimum, the second design consists of a primary leachate collection/removal system (LCR) (for landfills), a primary flexible membrane liner (FML), a secondary LCR, and a secondary composite FML/clay liner. The primary LCR system minimizes the leachate head acting on the primary FML and allows for the removal of liquids during the post-closure monitoring period. The primary FML serves the same function as in the first system and must be designed and constructed of materials to prevent the migration of leachate constituents greater than de minimis quantities into the liner throughout the postclosure care period. The secondary LCR system between the two liners should be designed and constructed to detect leaks in the primary liner, and collect and remove liquids for treatment through the post-closure care period. The secondary FML/clay liner is designed such that the two components act as one system that is designed and constructed to prevent greater than de minimis quantities of leachate through the composite liner for a time of less than the post-closure monitoring period.

Recent minimum technology requirements in the Federal Register, Vol. 52, No. 74, April 17, 1987, indicates that a permeable soil liner with a hydraulic conductivity of 10^{-7} cm/sec will have a minimum detectable leakage rate of approximately 86 gallons per acre per day. A composite liner consisting of an FML plus the soil layer will have a detectable leakage rate of only .001 gallons per acre per day. These limits would be appropriate for de minimis quantities. Unfortunately, no guidelines are given for detectable leakage rates through a typical FML. Thus a rigorous definition of de minimis is not available at present.

Acceptable double liner systems are not limited to the two designs discussed in the guidance documents and presented above. Alternate double liner designs will be acceptable if convincing performance equivalency can be demonstrated with the specifications in the guidance documents. A current alternative double liner design is shown in Figure 1.3 and incorporates a composite FML/clay liner in place of the primary FML liner in the guidance documents. The relative advantages and disadvantages of this system are currently under review by EPA. The addition of the clay liner increases the collection and removal efficiency of the primary FML, but also significantly retards the ability of the secondary LCR to detect leaks in the primary FML.

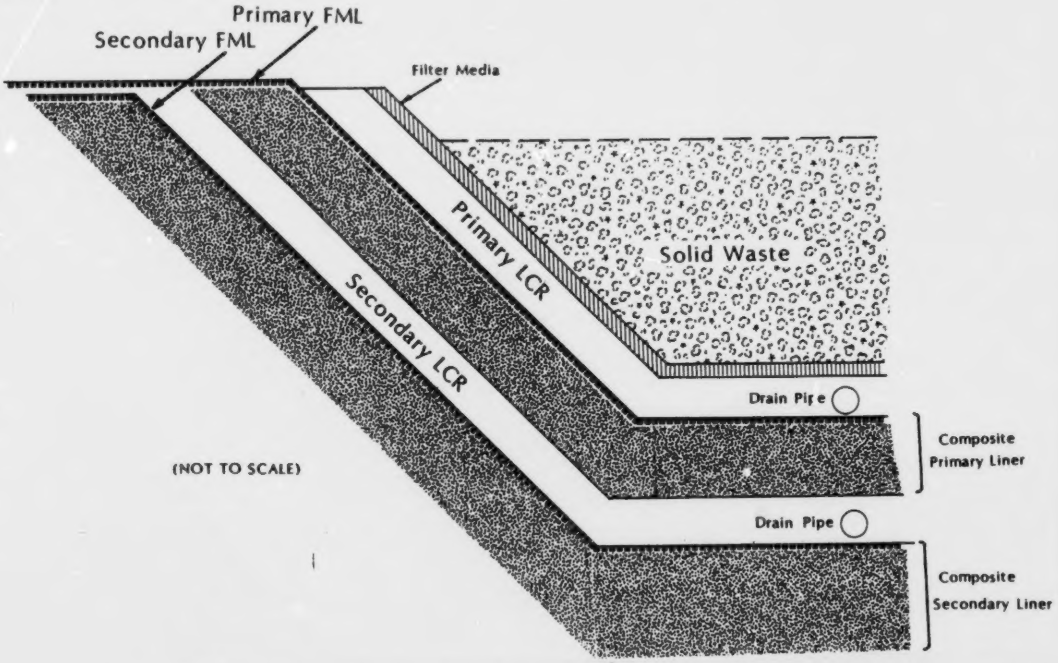

Figure 1.3 Composite/Composite Double Liner System

The EPA philosophy for minimizing the migration of hazardous constituents into the environment is a two-pronged liquids management program. One part of this management program is the use of technology to maximize the containment and removal of liquids from the unit before they can migrate into the environment. The two double-liner designs previously detailed are meant to function in this manner. An additional aspect of liquids management is the minimization of leachate generation through the use of design control and operational practice to minimize the amount of surface water entering the unit, particularly during the post-closure monitoring period. The final cover system must therefore prevent intrusion of surface water into the cell.

A proposed RCRA guidance (EPA, 1985c) final cover system for uncontrolled waste sites is shown in Figure 1.4 and consists of an optional gas collection layer or array, a low permeability layer consisting of at least 2 ft. of clay and a 20 mil flexible membrane cap (FMC), a surface water drainage layer, and a cover layer capable of supporting vegetation. The gas collection or clay layer must provide a sound working platform for placement of the overlying components. Specifications for soil materials to be used in the foundation layer typically include provisions for a maximum grain size and a requirement that they are free of debris that could damage the overlying FMC. The geometry of the gas collection system is influenced by the subcell structure within the total cell. The gas collection system functions to prevent the buildup of a signficant volume of gas vapors beneath the cover FMC. At facilities exposed to significant surface water or potential subsidence, the designer may opt to follow the design philosophy used in the liner system and use a double FMC system with a leak detection system between them. Monitoring of the witness drain would provide confirmation of the integrity of the upper FMC. The current draft MTG does not require a double FMC on facilities using a double FML.

The design considerations for the cover FMC differ significantly from the liner FML's. During its projected lifetime, the cover FMC will not be exposed to leachate but may experience significant environmental exposure and potential straining due to settlement within the waste material. Currently the cover FMC in many facilities is of the same material and gauge as the primary FML. This apparently was done to encapsulate the waste material and based on the belief that the 'permeability' of the FMC must be equal to or greater than the primary FML. Both practices may be conservative but do not reflect EPA guidance (Landreth, 1987). While greater discussion is given in Section V, it should be noted that current RCRA guidance provides for only one FMC at least 20 mil thick and does not require sealing of the FMC to the FML.

Atop the cover FMC, a surface water drainage layer is placed to drain liquid off of the FMC and away from the unit. This drainage layer may itself be composed of 3 subcomponents: (1) a bedding layer placed to protect the cover FMC, (2) the actual drainage layer designed to remove surface water, and (3) a filter layer that prevents movement of the vegetative cover soil into the drainage component. The final vegetative cover layer is required to support erosion resistant plant life and acts to shield the cover components from sun and weather related adversities.

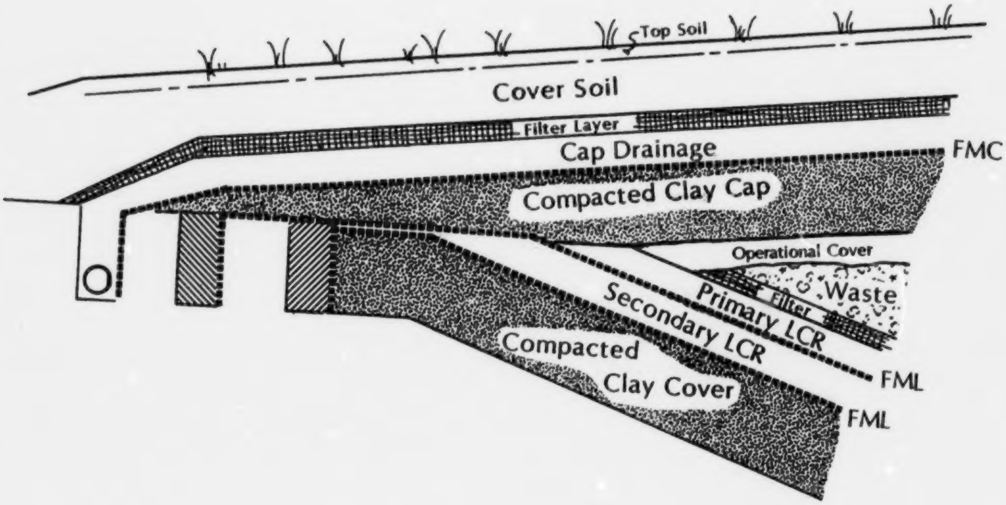

Figure 1.4 Proposed RCRA Cell Cap Profile

SURFACE IMPOUNDMENTS

Surface impoundments function similarly to secure landfills in that waste materials are contained to prevent the contamination of ground water at the site. The Surface Impoundment Assessment Report (EPA,1983) reported, however, that most wastes placed in a surface impoundment are waste waters being contained as part of a treatment process. A surface impoundment is not, therefore, necessarily the final resting place for the waste. Current regulations exclude from surface impoundments those wastes that are reactive or ignitable. Also excluded are EPA hazardous wastes F020, F021, F022, F023, F026, and F027 unless certain design, operating, and monitoring procedures are approved by EPA and included in the facility management plan (per 40 CFR Part 264.229).

Two options that influence design are given in the regulations for closure of surface impoundments. The first option is to remove or decontaminate all waste residues at closure. Under this option the surface impoundment can be constructed using a single liner (natural or synthetic) if it is located more than 1/4 mile from any underground source of drinking water. It must also comply with applicable ground water monitoring requirements for a permitted RCRA facility (40 CFR 264 Subpart K). The single liner must be designed to prevent breakthrough of the contained waste during the life of the impoundment. At closure, all waste and liner material contaminated by leakage must be removed. This option may be desirable for surface impoundments that hold process waste liquids temporarily.

The second impoundment design option is for in-place closure of facilities containing waste piles that cannot be economically removed. These impoundments must incorporate a double-liner system with a leak detection/collection system as previously described for a waste containment facility. Waste contained in the impoundment must have all free liquids removed. The remaining waste must be solidified and stabilized to provide a minimal bearing capacity. These facilities differ from secure landfills only in the nature of the wastes contained during their operational life. Current environmental laws (HSWA,1984) require that all surface impoundments must conform to double liner standards by November 6, 1988.

LONG TERM CONSIDERATIONS

Section VII reviews long term performance considerations for geosynthetics beyond the more obvious chemical compatibility considerations. Most of these concerns are also shared by more conventional 'geo' 'synthetic' systems such as buried plastic pipe and electrical cables. These considerations include microbiological degradation of the synthetics resulting from the consumption of plasticizers by the bacteria or fungus, and stress cracking /rupturing of the synthetic resulting from what should be allowable stress levels. The stress cracking/rupturing may be the result of deficiencies within the synthetic or may be caused by the applied stress and exposure to certain environmental conditions. Soil exposure tests have also shown that potential oxidation-reduction processes may occur in the synthetic as the result of burial. Obviously, when taken either separately or collectively, the above mechanisms will have a negative effect on the ability of a synthetic component to perform its function.

Unfortunately the lack of available data does not allow Section VII to provide much beyond pointing out such potential long-term considerations and reviewing proposed accelerated test procedures. No laboratory data currently exists to demonstrate the general impact of these long-term problems and certainly no standard tests are available to evaluate each concern in a given leachate.

SUMMARY

Geosynthetic components are now being used within all hazardous waste landfill disposal cells and substitute for an increasing number of natural materials within each cell. These geosynthetic components provide the following roles within the cell:

(1) Liner - all FML's and FMC's are geomembranes,
(2) Drainage - LCR systems may be constructed using geotextiles, geogrids, or composites to attain design transmissivities,
(3) Filter - geotextiles are commonly used to allow leachate to pass and yet prevent clogging of drain pipes within LCR systems and to protect the surface water drainage components,
(4) Bedding layer - a geotextile can be used to protect the cover geomembrane from damage related to placement of the surface water drain.

The design of these geosynthetic components is the primary focus of this document. Construction and long-term considerations are also reviewed. It should be noted, however, that chemical considerations have been excluded from consideration under this contract and are described elsewhere (Matrecon, 1987).

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SECTION II

SUMMARY

The design of hazardous waste containment cells and surface impoundments is currently a curious mixture of regulator-based minimum requirements, performance based engineered design, and empirical rules-of-thumb. This document emphasizes the analyses required to properly design a synthetic component based on calculated field conditions and laboratory measured component properties. Such synthetic components include the flexible membrane liners (FML), and synthetic drainage layers (LCR) used to replace layers of sand. The use of performance based design allows the designer/regulator to properly evaluate the true degree of protection against failure that regulatory minimums or rules-of-thumb provide. It is also apparent that our current level of knowlege regarding both long-term and in-situ performance of the synthetic components justifies conservative design practice and minimum criteria.

Each design consideration reviewed in this document is derived beginning with the specific equilibrium equations and then illustrated using typical application scenarios. For stress related considerations, the equations of equilibrium are based on 'free-body' diagrams that express both the direction and magnitude of forces acting at a given point in the component. The equations of equilibrium simply reflect the need for the sum of the forces to be equal to zero in a given plane for equilibrium (at-rest) conditions to exist. When a clear limit is known for the performance of the geosynthetic, a Design Ratio is defined as the ratio of the allowable material performance divided by the actual material service conditions calculated. A minimum value for the Design Ratio of one would then be required to prevent an undue amount of stress and/or strain of the component. Unfortunately, our ability to accurately define both the performance limits of the components and the service conditions requires the use of minimum Design Ratios considerably larger than one to ensure satisfactory performance. Suggestions are given for minimum values of Design Ratios in each analysis consideration. The designer is cautioned however to verify that the limiting value of the Design Ratio reflects the actual uncertainties associated with the particular design consideration. Each design consideration is demonstrated using typical application data. A Design Example sheet is provided for each consideration and includes a concise review of required material properties, analysis procedure development, and a typical application. It is unfortunately true that, at this time, very few actual field data exist to verify the accuracy of the solution provided for each consideration.

Beyond presenting the simple mathematics required to estimate the in-situ performance of a geosynthetic, this document attempts to review the current limitations in evaluating the actual performance of the synthetic under realistic field conditions. The test procedures referenced in this document are divided into index and performance tests. The index tests are developed to provide a means of quality control for the manufacture and are usually independent of actual field conditions. For membranes this includes such tests as density and absorbed moisture. Performance based tests try to simulate the true in-situ environment faced by the component as an essential part of the test process. Thus drainage components are tested for in-plane flow under normal stresses comparable to those generated by the weight of overlying waste and with actual field soils or other components adjacent to the component being tested. Performance tests are specific to the given field conditions of a single project.

A significant limitation in performance-based design lies in the lack of standardized test procedures that the designer can use. Many of the tests presented in this document and reviewed in the appendices are not formal standards and are currently in a state of change. In effect the designer is caught between the owner's needs and current ongoing research. The designer is cautioned to carefully review each laboratory test and satisfy in their own mind that it accurately portrays the in-situ conditions anticipated at the specific site.

The lack of recognized analysis and test procedures for the many design considerations is due to the relatively short time that many of the synthetic components have been available and to a similiar short time frame that the design of any waste facility has come under scrutiny. Koerner (1986) presented an estimated growth in the geosynthetic industry, Figure 2.1, that clearly shows the infancy of geosynthetic use. Quite clearly, the growth of the geosynthetic industry has occurred at essentially the same time as the growth in regulatory concern over hazardous waste facilities.

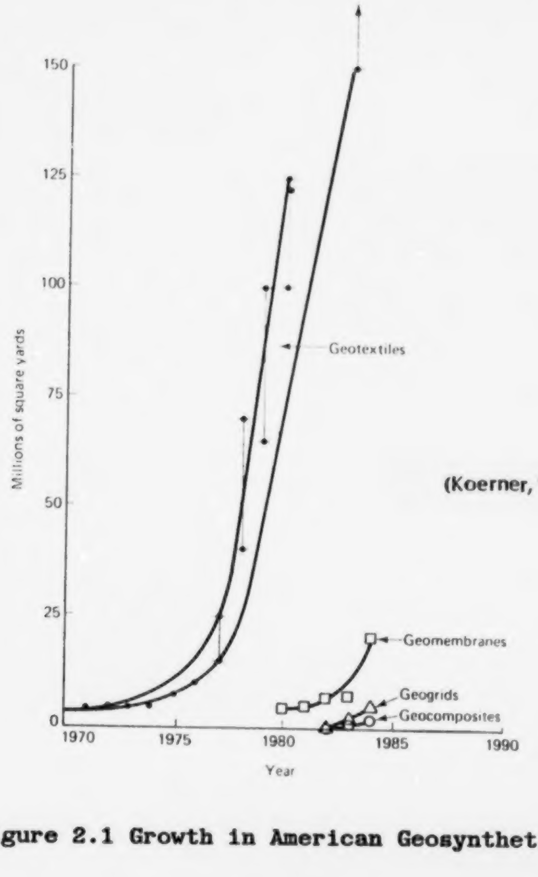

Figure 2.1 Growth in American Geosynthetic Market

DESIGN PRIORITIES

The design of a secure landfill requires a significant number of design considerations. The tables presented in this section attempt to weight design priorities for the components within the liner system. Design priorities for the liner systems are given on Table 2.1 to gain an overall perspective of the major geosynthetic design considerations. The priority ratings are very subjective and reflect the design and research experience of the authors for the "typical" application. The highest priority (1) design considerations reflect modes of failure that would be catastropic to the success of the facility. Thus for the FML any consideration that would lead to penetration or tearing of the membrane would be rated 1. A similiar rating of design considerations for the cap components is given in Table 2.2.

Table 2.1 Design Priorities - Liner System*

		Component	
Consideration	FML	LCR	Filter
Chemical Compatibility	1	1	1
MTG Criteria			
-thickness	2	2	3
-water vapor tran.	3	n/a	n/a
Mechanical Properties			
-tensile/yield	1	2	2
-friction	1	1	2
-anchorage	2	2	3
-internal shear	2	2	3
Hydraulic Properties			
-permittivity	n/a	n/a	1
-transmissivity	n/a	1	n/a
-clogging	n/a	2	1
Biological Properties	2	2	1
Construction Factors			
-wind	1	2	3
-puncture	1	3	3
-impact	1	3	2
-tear	1	3	3
-seams	1	2	2
Long Term Factors			
-Env. Stress Crack/Rupt	1	3	3
-durability/aging	1	1	1
-disturbances	2	2	2

* (1-high, 3-low, n/a-not applicable)

Table 2.2 Design Priorities - Cap System*

Consideration	GAS VENT	FMC	SWCR	Filter
Chemical Compatibility	2	3	3	3
MTG Criteria				
-thickness	2	2	3	n/a
-water vapor trans.	n/a	2	n/a	n/a
Mechanical Properties				
-tensile/yield	2	1	2	2
-friction	2	1	1	1
-anchorage	n/a	3	3	3
-internal shear	3	3	3	3
Hydraulic Properties				
-permittivity	2	n/a	n/a	1
-transmissivity	1	n/a	1	n/a
-clogging	3	n/a	1	1
Biological Properties	n/a	3	2	3
Construction Factors				
-wind	3	1	2	3
-puncture	3	1	3	2
-impact	3	1	3	2
-tear	3	1	3	3
-seams	3	1	3	3
Long Term Factors				
-Env. Stress Crack/Rupt	3	2	3	3
-durability/aging	2	2	2	2
-disturbances	2	1	1	1

* (1-high, 3-low, n/a-not applicable)

RESEARCH NEEDS

Close comparison of the highest priority design considerations given in Tables 2.1 and 2.2 with the design examples in this document reveals that many high priority design items are not currently well understood. This is particularly true of biological and all long-term considerations but is also true of such basics as the definition of the correct stress-strain characteristics for FMLs. Immediate research needs resulting from such a comparison include the following:

> Better define the stress conditions in FMLs near penetrations, sumps and in corners to determine if the designs should be based on biaxial or confined tensile test data from the FML.
>
> Verify that rates of biological growth on filter fabrics will not prevent the flow of leachate into the collector system.

Define operational procedures that will minimize the production of waste generated gases and develop analytical methods for predicting the rate at which gases will be generated.

Develop permittivity and clogging tests that better replicate the in-situ conditions experienced by the geosynthetic in the field.

Significant in its absence is verification of the long-term effect of low concentrations of many hazardous wastes on the physical properties of the components. This document does not, however, deal with chemical-related considerations.

REFERENCES - SECTION II

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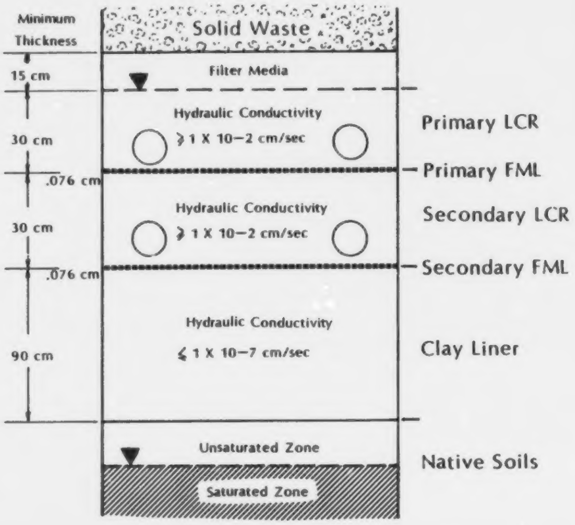
SECTION III

DESIGN OF COMPONENTS BENEATH CELL

COMPONENT FUNCTIONS

Geosynthetic components beneath the hazardous waste materials within a hazardous waste landfill cell provide the primary separation between leachate generated within the cell and the surrounding hydrogeologic environment. In the draft MTG (EPA,1985), this profile consists of two subsystems, each with a flexible membrane liner (FML) and leachate collection/removal (LCR) system. The draft MTG recommended cell liner profile is shown on Figure 3.1. The FML and LCR nearest to the waste are the primary system and function exclusively to contain leachate. The primary LCR must be designed to allow no more than 1 foot of head to act on the primary FML at any given time. The primary LCR also plays an important role during operation of the cell when the primary LCR is used to drain surface water collected within the cell and to protect the primary FML.



Minimum Thickness
Solid Waste
15 cm
Filter Media
Hydraulic Conductivity
≥ 1 X 10−2 cm/sec
30 cm
Primary LCR
.076 cm
Primary FML
Hydraulic Conductivity
≥ 1 X 10−2 cm/sec
30 cm
Secondary LCR
.076 cm
Secondary FML
Hydraulic Conductivity
≤ 1 X 10−7 cm/sec
90 cm
Clay Liner
Unsaturated Zone
Saturated Zone
Native Soils

Figure 3.1 Profile of MTG Double Liner System

The additional FML and LCR systems are for the secondary containment system. Leachate passing through defects in the primary FML is detected in the secondary LCR and removed. The secondary LCR is commonly referred to as a witness drain since it bears 'witness' to the integrity of the primary FML. The secondary LCR system must also be designed to prevent more than one foot of head to act on the secondary FML, while also providing a rapid detection of leachate passing through the primary FML. As will be shown in this section, the dual requirements of rapid detection and removal of excess leachate can produce conflicting design criteria.

LEACHATE COLLECTION/REMOVAL SYSTEMS

Leachate is defined as "any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous waste" (40CFR 260.10). Leachate is generated by the draining of liquids from within the waste mass and from the infiltration of water from the surface of the cell. Additionally, the LCR system is commonly used during operation of the facility to remove surface water that has drained into the cell. This water is assumed to be leachate. The quantity of leachate generated depends on the types of waste, operational procedures, cover efficiency, and water balance within the cell at a particular time. Liquid input to the cell includes liquids in the deposited waste and surface liquids resulting from precipitation or surface water. Liquid output includes evaporation, transpiration, and seepage from the facility (Bass, 1986). Techniques for estimating leachate volume are discussed by Schroeder, et al (1984).

Minimum Technology Guidance (MTG) provided by EPA (1985) provides technical guidance on minimun design standards for LCR systems. Specific guidance on leachate collection systems design includes the following:

- A granular drainage layer should be at least 30 cm (12 in.) thick with a minimum hydraulic conductivity of 1×10^{-2} cm/sec and a minimum bottom final slope of 2% after long term settlement.
- Synthetic drainage layers may be used if they are equivalent to the granular design, including chemical compatibility, flow under load, clogging resistance, and protection of the FML.
- The drainage layer should include a pipe network which is designed to efficiently collect leachate. The spacing of the pipe network should be sufficient to ensure that no more than 1 foot of leachate will collect in the LCR. The pipe and drainage layer materials should be chemically resistant to the waste and leachate. The pipe should also be strong enough to withstand expected loading.
- A filter layer (granular or synthetic) should be used above the drainage layer to prevent clogging.
- The LCR system must cover the bottom and sidewalls of the unit.

Geosynthetic components within the LCR can, therefore, include a synthetic drainage layer used to replace the granular layer or the pipe network itself, and filter fabric designed to prevent clogging of the drain pipes or synthetic drainage lines.

Transmissivity Criteria

A geosynthetic system used to replace the granular drainage layer must provide either the minimum planar flow capacity defined by the Minimun Technology Guidance or that required to maintain the liquid levels over the liner at less than 30 cm (1 ft). The planar flow of liquids through the LCR is defined by Darcy's equation as

$$q = K_p \, i \, A \qquad \text{Eq(3.1)}$$

$$q = K_p \, [dh/L] \, W \, t \qquad \text{Eq(3.2)}$$

where q is the flow rate, K_p is the permeability coefficient in the plane of the geosynthetic, dh is the head loss, L is the flow length, W is the width of the drainage layer, and t is the thickness of the drainage layer. Because the thickness of most geosynthetic systems is difficult to quantify, Equation 3.2 is commonly expressed as

$$q = [K_p \, t] \, [dh/L] \, W \qquad \text{Eq(3.3)}$$

$$q = \theta \, [dh/L] \, W \qquad \text{Eq(3.4)}$$

where θ is defined as the transmissivity of the drainage layer. Substituting minimum drainage layer properties as defined in the current MTG guidance criteria (30 cm thickness and a minimum permeability of 1×10^{-2} cm/sec) results in a minimum required drainage layer transmissivity of 3×10^{-5} m^2/s.

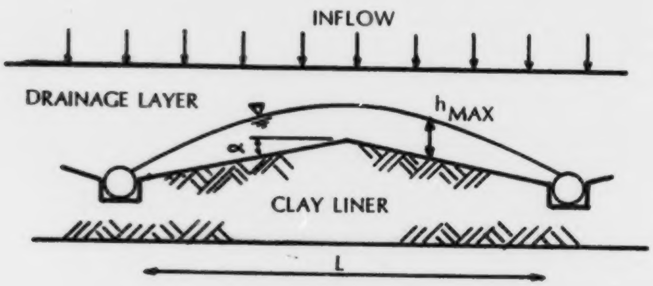


Figure 3.2 Leachate Head vs Collector Pipe Spacing

The minimum transmissivity of an LCR may also be controlled by the requirement to maintain no more than 30 cm (1 foot) of leachate head acting on the liner at all times. Conventional granular leachate control systems are designed so that the maximum one foot head acting on the FML remains within the drain layer. The head acting on the FML is controlled by the rate at which leachate is being generated and collected within the system, the hydraulic properties of the LCR, and the spacing of the collector pipes within the LCR. These parameters are shown on Figure 3.2. The maximum head acting on the FML for a uniform rate of leachate generation is given by

$$H_{max} = \frac{L\sqrt{c}}{2} \left[\frac{\tan^2\alpha}{c} + 1 - \frac{\tan\alpha}{c} \sqrt{\tan^2\alpha + c} \right] \qquad \text{Eq(3.5)}$$

where c is defined as the inflow rate, q, divided by the hydraulic conductivity of the LCR. The greatest uncertainty associated with this calculation is accurately estimating the rate of leakage generated at the LCR boundary. While beyond the scope of this document, methods for estimating this quantity have been detailed by Wong(1977), Scharch(1981), and Demetracopoulos(1984). This method has been supplemented by an alternate procedure proposed by Moore (EPA,1983b) that is based on the percolation velocity of the leachate. The maximim leachate head using this method is given by

$$H_{max} = \frac{L}{2n} \left[\sqrt{\frac{e}{K} + \tan^2\alpha} \;\; - \tan\alpha \right] \qquad \text{Eq(3.6)}$$

where e is the percolation velocity based on conversion of the annual percipitation rate into a uniform velocity (cm/sec) and K is the hydraulic conductivity of the layer. The percolation velocity is equivalent to the inflow rate but is based on the assumption of a given percentage percolation of precipitation into the cell while the inflow rate is influenced by soil permeability, waste characteristics, etc. In these designs, the leachate phreatic surface remains within the LCR system.

Geosynthetic LCR systems are very thin when compared to equivalent-flow granular LCR systems. Thus the one foot of head that may act on the FML would not physically remain within the synthetic LCR layer. The one foot head must be interpreted as a design-applied pressure that is assumed to act at the interface between the synthetic LCR and the overlying soil. The required transmissivity of a synthetic LCR is computed by equating the rate of leachate inflow to the LCR with the flow capacity of the LCR. For a of synthetic LCR, the volume of leachate entering the system is equal to

$$Q_{in} = q_{in}\, L\, W \qquad \text{Eq(3.7)}$$

where q_{in} is the inflow rate of leakage generated at the waste LCR boundary, L is the effective length of the LCR and W is the width. The quantity of leachate that can flow through the LCR system is given by

$$Q_{LCR} = 2\,T\,[1 + L\sin(\phi)/2]/L \qquad \text{Eq(3.8)}$$

where ϕ is the slope of the LCR. Equating the leachate inflow and flow capacity of the LCR, an expression for the minimum value of transmissivity of the LCR is obtained as

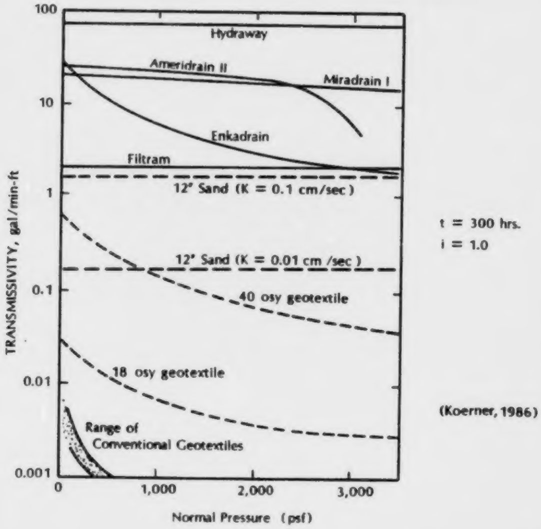
$$\theta = \frac{qL^2}{4h_{max} + 2L\sin\phi} \qquad \text{Eq(3.9)}$$

The percolation velocity e can be substituted for q. Example 3.1 details the computation steps required to evaluate the mimimum transmissivity based on percolation velocity and leachate inflow criteria.

An additional design criterion for the primary LCR may be a flow criteria based on the need to remove surface water during operation. The design will be influenced by both the details of the actual operation and the design precipitation. The inflow into the system is estimated using runoff calculations of the form (EPA, 1986a)

$$Q = C \; I \; A \qquad \text{Eq(3.10)}$$

where Q is the surface water inflow, C is the runoff coefficient, I is the average runoff intensity, and A is the surface area. The surface water inflow is calculated and then the minimum transmissivity of the LCR is calculated using the analysis shown in Example 3.2.



t = 300 hrs.
i = 1.0

(Koerner, 1986)

Figure 3.3 Elastic Compression Curves - Transmissivity

An important consideration in the design of a geosynthetic LCR system is the influence of large normal loads on the transmissivity of the system. Reduction in transmissivity can occur initially due to the elastic compression of the synthetic layer, and over a period of time due to compressive creep characteristics within the synthetic LCR. Transmissivity curves showing elastic compression for a range of geosynthetics are shown on Figure 3.3. These reductions are instantaneous and influence the capacity of the system even during construction. Also note the extreme variability of the products. Compressive creep occurs over a period of time under constant normal load conditions. The creep may relate to plastic properties of the polymer used in the LCR, to geometric instabilities in the structure of the synthetic LCR, or to the intrusion of soil caused by creep in the overlying filtration geotextile.

The transmissivity of a geosynthetic LCR is currently measured using flow devices that require a 12 inch square LCR sample and measure the flow rate of water through the system at various head losses. Current testing by the authors and Williams(1987) has shown that the transmissivity of the synthetic LCR can be reduced by an order of magnitude during the first 30 days of service if a soil is immediately adjacent to the LCR. As discussed above, this reduction over time is caused by the intrusion of the adjacent geosynthetic into the flow core and by creep related collapse of the core. It is therefore very important that the laboratory test be performed under boundary conditions that closely replicate the actual field conditions. In particular, the test for the primary LCR should include soil adjacent to the LCR and not use metal plates on both faces. The secondary LCR is normally between two FMLs and therefore may be tested between sheets of such material. The elimination of the soil boundary will eliminate creep penetration of the soil and the geotextile. Because of this, the minimun suggested Design Ratio for the primary LCR is greater than that for the secondary LCR system. Details of the transmissivity test are given in Appendix D.

Test data defining the time dependence of the transmissivity should be determined. This laboratory data will reflect the combined influence of all the creep mechanisms. Example 3.3 illustrates the technique used to evaluate the ability of an LCR system to provide the minimum required transmissivity over a design time period. The creep analysis technique used in this example may not be appropriate for composite LCRs that use a formed internal core. These systems may have multiple creep phenomena occurring simultaneously with collapse limits associated with one or more of the mechanisms. While the long-term transmissivity for such composite systems obviously could be evaluated by running a conventional transmissivity test for an extended duration, laboratory difficulties, such as biological growth, and test machine availability may preclude such testing. An alternate solution is to analyze the service stress in each component and predict the long term performance of each component. Procedures for such calculations are based on measured long-term creep properties of each generic component (Shestra and Bell, 1982). When possible, the designer should compare the limited laboratory creep data with that predicted by the analytical model developed by the manufacturer.

The design time period must extend over the projected monitoring period for the facility. A minimum period of time would obviously be the projected operational life plus the 30 year post-closure monitoring period. In anticipation of potential extended monitoring, it is recommended that a 50-year minimum design life be used in projecting the service life of a synthetic LCR system.

Filter Criteria

To ensure effective operation of the LCR over its design life, the designer must ensure that leachate can freely flow into the system and that the system does not become clogged due to the inflow of fines from the surrounding waste and soil layers. Specific attention must be given to the horizontal boundaries between the LCR and adjacent soil or waste deposits and around the collector pipe network within the LCR. Two types of soil filter systems commonly used are graded granular filters and geotextile filters. Granular filters rely on a combination of soil layers having a coarser gradation in the direction of seepage to prevent movement of soil particles. Geotextile filters were introduced only in the last 15 years and rely on the fine and uniform porosity of the fabric to prevent the movement of soil fines.

The ability of leachate to freely flow through a geotextile filter is influenced by the permittivity of the geotextile and the head acting on the leachate. Permittivity is defined here as K/t, where K is the permeability of the geosynthetic and t is its thickness. It is reasonable to assume that in fabrics having a significant thickness, nonwovens in particular, the permittivity will decrease with increasing normal load. The only approved permittivity test, ASTM D4491, does not provide for the application of normal forces. Design Example 3.4 demonstrates the use of permittivity test data in evaluating the flow characteristics of a geotextile. Be cautioned, however, that large normal loads can reduce the permittivity value significantly thus high Design Ratios are required.

Filter design criteria for geotextiles are still evolving. Current analytical methods are based on an Apparent Opening Size (AOS) for the geotextile. The AOS of the material is usually evaluated in the laboratory using a test procedure developed by the Corps of Engineers (Calhoun,1972). This test measures the percent of uniform glass beads retained on the fabric for a range of bead sizes. The bead size having only 5% retained is defined as the O_{95} or AOS of the geotextile. There are a number of techniques for evaluating the soil retention capabilities of a given geotextile, all of which use soil particle size characteristics compared to the AOS of the fabric. The simplest methods (Koerner, 1986) examines the percentage of soil being retained on the #200 sieve (= 0.074 mm). Accordingly (Task Force 25, 1983), the following recommendations are made:

1. Soil <50% passing the No. 200 sieve
   AOS of fabric > No. 30 sieve (0.59 mm)

2. Soil >50% passing the No. 200 sieve
   AOS of the fabric > No. 50 sieve (0.297 mm)

Slightly more restrictive criteria have been proposed (Carroll, 1983) (Chen, 1981) based on the d_{85} of the soil sample, where d_{85} is the particle size of the soil at which 85% of the particles are finer. These criteria are expressed as follows:

$$\frac{O_{95}\text{ of the geotextile}}{d_{85}\text{ of the soil}} < 2 \qquad \text{Eq(3.11)}$$

and

$$\frac{O_{95}\text{ of the geotextile}}{d_{15}\text{ of the soil}} > 2 \qquad \text{Eq(3.12)}$$

The first criterion is intended to prevent particles of soil from flowing through the geotextile while the second criterion is intended to prevent the clogging of the geotextile.

A more conservative filtration design approach (Giroud,1982) includes consideration of grading by including the coefficient of uniformity, CU, for the soil in the criteria. The coefficient of uniformity is defined as the ratio of the d_{60} to the d_{10} of the soil. The more uniform a soil in particle size, the smaller is the CU. Note that gap-graded soils cannot be identified using CU criteria. The relationships proposed to predict excessive loss of fines during filtration are then given by

Relative Density, Dr	$1 < CU < 3$	$CU > 3$
Loose(Dr<50%)	$O_{95} < (CU)(d_{50})$	$O_{95} < (9d_{50})/CU$
Intermediate (50%<Dr>80%)	$O_{95} < 1.5(CU)(d_{50})$	$O_{95} < (13.5d_{50})/CU$
Dense(Dr>80%)	$O_{95} < 2(CU)(d_{50})$	$O_{95} < (18d_{50})/CU$

Where Dr is relative density, d_{50} is the grain size corresponding to 50% passing, O_{95} is still equal to the AOS of the geotextile, and CU is the coefficient of uniformity(d_{60}/d_{10}) of the soil.

It should be noted that many designers argue that a filter layer is not necessary when the quantity and loading rate of fines into the drainage layer are small enough that the performance of the drainage layer is not affected. Consideration of the anticipated particle size and flow velocities of the leachate may indicate that fines will be effectively flushed from the system without the need for a filtration layer. For typical waste disposal cells it is reasonable to assume that flow quantities and velocities will be low during post-closure monitoring, but may be large during actual operation of the facility. Additionally, the AOS test, which serves as the basis for clogging criteria, does not accurately portray the physical properties of a heavy nonwoven fabric. In these fabrics, the glass beads used to conduct the test become entrapped due to thickness and not porosity. Draft MTG (EPA,1985) recommends the use of a granular or synthetic filter layer over the LCR to prevent clogging of the LCR. Example 3.5 presents an evaluation of a geotextile for filtration criteria.

The potential for clogging of the filter must be evaluated if the long-term function of the filter is to be ensured. Acting as a filter, the geotextile will trap soil particles within its pore space and could eventually be blinded or clogged by these entrapped particles. Clogging potential can be evaluated in the laboratory using the gradient ratio test. This test evaluates a hydraulic gradient across the fabric. If the gradient ratio predicted by this test exceeds 3, there is potential for clogging. Additionally, the gradient ratio test device can be used to evaluate the flow versus time relationship to evaluate the terminal or long-term flow capability. Design Example 3.6 demonstrates the interpretation of gradient ratio and long-term flow data for evaluating clogging potential.

Another approach to evaluating clogging potential is to avoid soils or field conditions that have been shown to have a high likelihood of producing clogging in a geotextile: 1) cohesionless sands and silts with gap-graded particle size distributions and high hydraulic gradients, 2)permeating liquids having very high values of alkalinity, e.g. pH > 11, and 3) situations where dynamic or pulsating fluid action occurs across the plane of the geotextile filter. Of these three situations, the first two are of most concern for waste facilities. Gap-graded soils can be readily identified and should be avoided adjacent to any geotextile filter layer.

The greatest danger of gap-grading occurs if unwashed sands or gravels are used to form the LCR and a fabric wrap is placed around the collector pipe network. For this reason, all sands or gravels used within a LCR must be washed to remove the fines.

Strength Criteria

LCR systems must extend beneath the entire cell. As such, the LCR system will be constructed on the sideslopes and be subjected to shear stresses generated by the sliding potential of materials placed on top of the LCR. These sliding stresses can place the synthetic LCR in tension and produce in-plane strains. Additionally, the LCR may be subjected to significant in-plane strains generated by the elongation of the LCR due to settlement of the underlying subgrade. Both in-plane strains produce tensile stresses that can disrupt or rupture the LCR. Geosynthetic LCR systems are very thin when compared to a granular LCR system, and a greater potential for disruption of flow exists in the synthetic LCR.

Sideslope stresses generated within the LCR by overlying materials are calculated in Example 3.7. In general the friction between the LCR and the FML will be very low and result in the LCR having to support the overlying materials. The ultimate strength of the LCR material is determined in the laboratory using a wide-width tensile test procedure. The friction between the soil-LCR and LCR-FML is also determined in the laboratory using a large direct shear test machine (Martin,1984). The Design Ratio calculated in Example 3.7 relates only to complete failure of the LCR in tension. The shear stresses acting on the LCR will also generate significant elongation in the LCR and can produce undesirable deformation within the side-slopes. The sliding evaluation is particularly critical if a composite soil/FML primary liner is being used in the facility.

Settlement of the waste within the landfill will generate shear stresses on the surface of the primary LCR in the same manner that consolidation of soils produces down-drag forces on piling. The consolidation of the waste mass within the facility is due to the weight of overlying waste and the loss of liquids in the form of leachate. The waste matter at the bottom is nearest the drainage face and under the largest normal load. Thus, the waste will consolidate from the bottom first. This consolidation will produce surface settlement of the waste and transfer shear stresses to the LCR as the waste matter attempts to move downward. Obviously the amount of shear stress generated will initially be controlled by the amount of settlement that has occurred along the sidewalls of the facility. For the shallow slopes (>3:1) used in most facilities very little settlement should be evident at the sideslope. For steeper slopes(>2.5:1) some settlement may occur at the sideslope. Example 3.8 shows the limiting stress that would be produced in the LCR if it was designed to resist settlements. These stress levels are clearly excessive. Fortunately, however, the analysis of Example 3.8 neglects to examine the strain compatibility between the LCR and the settling waste. The limit analysis in Example 3.8 would be appropriate if the FML was very stiff or if the settlement was very large. An analysis that is based on strain compatibility between the LCR and the settling waste is given in Example 3.9. This analysis is more appropriate for the small edge settlements, and flexible LCRs anticipated. The limitation of the strain compatibility analysis is our inability to analytically predict edge settlements.

Primary Versus Secondary LCR Systems

The design of the secondary LCR system must consider that this system will perform the same functions as the primary LCR with the following exceptions:

1) The secondary LCR system does not normally handle the volume of leachate and surface water runoff that the primary LCR must drain during operation and post-closure.

2) The secondary LCR acts as a witness drain for the primary FML and must provide a rapid collection/detection of leachate.

3) The secondary LCR must support the overlying primary FML and LCR systems and loads placed on them, see Example 3.10.

The first two factors indicate that the secondary LCR system must have the minimum capacity required to remove leachate in case of failure of the primary FML. An overly large capacity within the secondary LCR could delay the detection of leachate. Estimating detection time of the secondary LCR system is demonstrated in Example 3.10. Balancing the opposing needs of rapid leak detection and flow volume may be based on management decisions.

Within the third exception above, the sliding evaluation is particularly critical if a composite soil/FML primary liner is being used in the facility. Example 3.11 evaluates the secondary FML for the composite primary FML condition. Note that significant stresses are generated within the LCR unless an increase in the FML/LCR friction angle can be realized. Conventional FML materials, such as HDPE, provide a very low coefficient of friction between the primary FML and the secondary LCR systems. Efforts to increase this frictional bond have not been successful to date.

FLEXIBLE MEMBRANE LINERS (FML)

Flexible membrane liners are composed of membranes made primarily of polymeric materials. These synthetic membranes are essentially impermeable and are meant to control the flow of leachate out of the cell. In view of their placement within the soil, these membranes are referred to as geomembranes. The performance of the geomembrane is dependent upon the following factors:

1) Sufficient thickness of membrane must be used to achieve *de minimis* levels of leakage. Under draft MTG, a minimum thickness of 30 mils is required for FMLs in secure landfills and 45 mils for the FMLs in a surface impoundment or when it will be exposed to weather for some time. Note that the thickness of scrim or other reinforcement is included in computing thickness under MTG criteria.

2) Stresses that develop during installation and subsequent use must not physically harm the membrane.

3) Seams that bind panels of geomembrane together must not leak and must be physically strong in both shear and peel.

Minimum seam strength requirements must be established.

4) Placement of the FML on the soil and cover on the FML must not cause localized penetration of the membrane. Specific minimum criteria for bedding materials as provided in MTG.

5) The FML must be securely anchored so that operational loads do not dislodge the FML.

6) Construction practice must protect the FML from wind, ice, and other environmental factors that can damage the membrane.

7) The polymeric material forming the FML must be chemically stable when exposed to leachate.

8) Long-term considerations must be anticipated.

The first five factors will be discussed in this section, the sixth factor is discussed in Section V, the seventh factor is beyond the scope of this document but is discussed elsewhere (EPA,1983b), and the last factor is the subject of Section VII.

FML Vapor Transmission

The permeability of most common polymeric membranes is sufficiently low so that it cannot be evaluated using conventional permeability testing procedures. The flow rates through conventional fixed or falling-head permeameters would be so small that either evaporation would destroy the leakage or extremely high gradients would be required to produce measurable flows. Thus the FML is essentially impermeable to fluid flow based on Darcy's law. The gas vapors from leachate can, however, diffuse across the FML driven by vapor pressure gradients. This diffusion process is quantified using Fick's first law (Lord and Koerner, 1984). The diffusion constant can be measured using a water vapor transmission test (WVT), ASTM E96. The diffusion rate is measured in the WVT test using water vapor as the permeant. The test specimen is sealed over an aluminum cup having either water or a desiccant in it, and a controlled relative humidity difference is maintained on either side of the membrane. The weight gain or loss of the aluminum cup and membrane is monitored for 3 to 30 days. Further details of the test are presented in the appendix.

Both Darcy's Law and Fick's first law are both first order ordinary differential equations. Thus the diffusion process measured in the WVT test can be modeled as a psuedo-Darcian flow. Thus, while recognizing that the test is based on diffusion and not flow, the WVT can be expressed in terms common to Darcy's equation as follows:

$$Q = k_{psuedo}\ i\ A\ t \qquad \text{Eq(3.13)}$$

or

$$k_{psuedo} = [\ Q/tA\ ]\ /\ i \qquad \text{Eq(3.14)}$$

where [Q/tA] is the WVT. The permeance or k_{psuedo} of the membrane is defined as the WVT divided by the vapor pressure gradient, dh, that existed on the FML during testing. Further defining the gradient, i, in Expression 3.10, the relationship of permeance to pseudo-permeability can be shown as

$$k_{pseudo} = [\ Q/tA\ ]\ /\ [\ dh/l\ ] \qquad \text{Eq(3.15)}$$

$$k_{pseudo} = [\ Q/tAdh\ ] \times l \qquad \text{Eq(3.16)}$$

where [Q/tAdh] is the permeance and l is the thickness of the FML. Results of a WVT test are presented in Example 3.12 and converted into a conventional pseudo-permeability value of use to a designer.

While no membrane is totally impermeable, the designer must insure that the FML allows no more that de minimis leakage under the maximum 1 foot head condition. De minimis is assumed in this document to equal 1 gallon/acre/day of leakage. Verification of this fundamental design requirement is shown in Example 3.13. While it is assumed that manufacturers of FML panels would supply the WVT test data required to perform this check, it should be noted that the calculated Design Ratio is typically large.

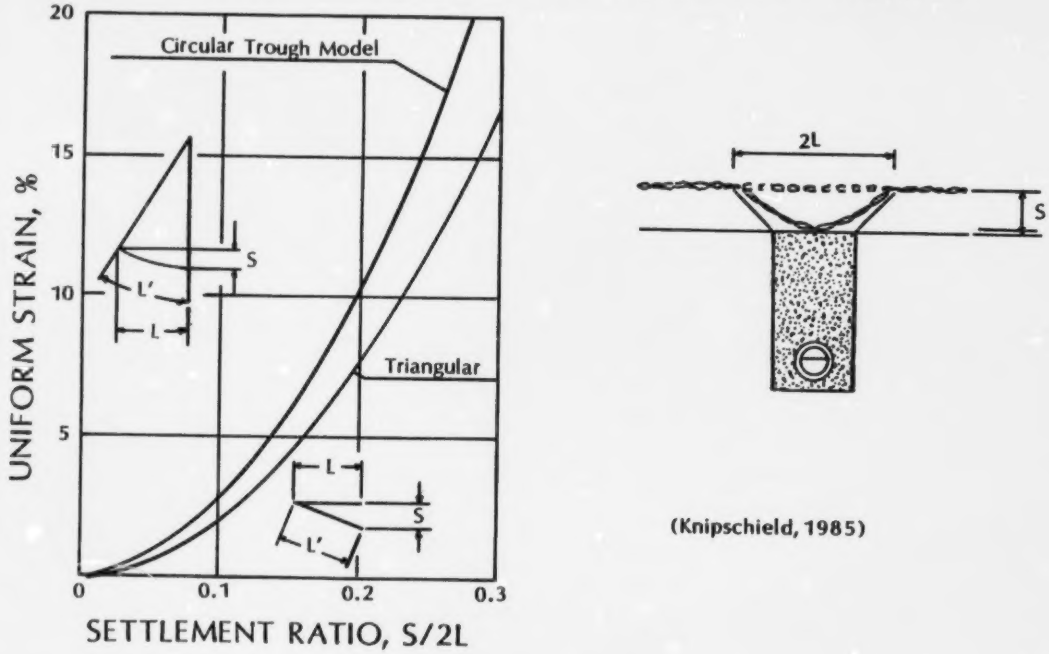
FML Stresses

Flexible membrane liners must support their own weight during installation, resist down-drag forces generated as interior layers or cells are built, and survive deformations from potential settlement of the contained waste mass. Membrane tensile strengths for single ply, unreinforced membranes can be determined using small 'dog bone' specimens tested at a constant strain rate. These materials will show a linear increase in yield force with thickness of the FML. Reinforced and multiple ply membranes may be more sensitive to scale effects in testing and may require the use of a wide-width test device. For reinforced and composite membranes, the yield stress is not a linear function of thickness.

During construction of a cell, the FML is draped from the anchor trench to the bottom of the cell. The tensile forces generated within the FML due to self-weight are calculated in Example 3.14. This consideration is normally critical only for unreinforced membranes that have an allowable or yield stress of less than 1000 psi and on steep side slopes. A relatively large Design Ratio in this mode does, however,minimize elongation or stretch of the FML during installation.

Tensile stresses can be generated in the FML and LCR during placement of waste against the cell sidewall. The waste can move downward as a block as modeled in Example 3.15 or a deeper failure surface may develop. In both modes, forces are transmitted to the FML through the LCR in response to the downward movement of the waste. These forces transmitted to the FML can be limited if there is a low coefficient of friction between the LCR and the FML. When synthetic LCR systems are used, this friction is low enough that only minimal force can be transferred to the FML. Example 3.15 uses a granular LCR system to demonstrate the extreme case. It would appear that down-drag forces both during operation and long term are best minimized by using a synthetic LCR over the primary FML. The coefficient of friction between membranes and either geonet or geotextile is very low so that larger down-drag forces cannot be transferred to the primary membrane.

The use of a composite primary liner (FML plus clay layer) can produce extreme tensile stresses in the secondary FML. The clay portion of the composite primary liner may produce significant shear imbalances in the secondary FML resulting in high tensile forces within the primary FML. Critical design conditions exist during construction if the clay portion is constructed much thicker than design and then trimmed. As shown earlier in Example 3.11, the tensile forces generated by the weight of the composite primary liner cannot reasonably be carried by currently available synthetic LCRs and FMLs in tension. The forces must be carried by the surface friction and adhesion forces that develop on the surface of the synthetic components. Unfortunately, available FMLs have a very low adhesion and coefficient of friction with both soils and synthetic LCR components.



(Knipschield, 1985)

Figure 3.4 Settlement Trough Models

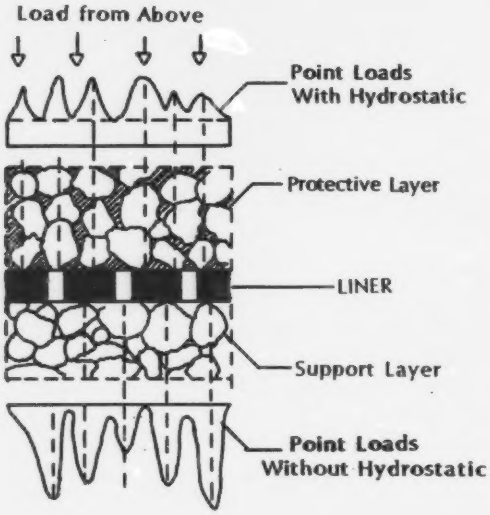
In addition to waste settlement, strains can be induced in the FML from localized settlement beneath the FML. Such settlement may result from improperly compacted fill around collection pipes or soft zones in the underlying subgrade. The strains induced in the FML can be estimated using a simple trough model that relates the depth and width of the settlement feature to the average strain in the membrane. This relationship is shown on Figure 3.4. Knipshield(1985) has suggested that the strain given by the trough model should be reduced to reflect the additional elongation that occurs in the FML immediately adjacent to the trough. This additional deformable length is given by

$$x = [\ f_y \ d\ ]/[\ 2\ A\ ft\ ] \qquad \text{Eq(3.17)}$$

where f_y is the tensile yield or allowable strength of the FML, d is the sheet thickness, A is the normal stress acting on the sheet, and ft is a force transmission factor defined by Knipshield to be 0.35. The ft factor is the friction coefficient of the soil to the FML and should be verified for the particulars of a given field situation. The strain given by Figure 3.4 must be decreased to reflect the additional deformation. The corrected strain is given by

$$\text{strain} = dl / [L + 2x/2] \qquad \text{Eq(3.18)}$$

where dl is the increase in membrane length obtained using Figure 3.4, L is the original width of the settlement feature, and x is the additional deformable length. Example 3.17 demonstrates calculation of localized settlement induced stresses in an FML. This analysis assumes that the FML within the settlement area deforms uniformly. Knipshield indicates that this condition is fulfilled for a FML having a high elastic modulus and a minimum thickness. For HDPE the minimum thickness is given as 80 mil (2mm).



(Knipschield, 1985)

Figure 3.5 Compressive Stress Model

Pressure forces act on the FML due to the weight of the waste and soil mass on top of it. This pressure has been assumed to act as an even pressure in the previous calculations. In reality, however, the normal stress acting on the FML will be influenced by the particulate nature of the soil above and below the FML. The particulate nature of the adjacent soils produces concentrations of normal stresses as shown on Figure 3.5. The very large stress peaks can lead to shear failure of the FML and penetration of the soil particles into the FML. Support and protective layers must be arranged to minimize the peak normal loads. West German practice is to arrange the adjacent soils in normal grain, rough grain, and fine grain structure adjacent to the FML. Evaluation of the impact of such normal stresses must be performed in the laboratory using site specific soils. If the FML cannot be protected by grading the soil, then protective layers of geogrid or geonet must be used.

FML Seaming

Methods used to seam polymeric membranes depend upon the composition of the membrane and the environment the membrane is placed in. For hazardous waste disposal facilities, general practice is to avoid any bonding method that will leave a residue of volatile organic solvents that may eventually be confused with leachate. This consideration aside, the common methods for seaming FMLs include adhesive or solvent bonding, thermal bonding, extrusion or fusion welding, vulcanization, and mechanical methods. Typical seam configurations used are shown on Figure 3.6.

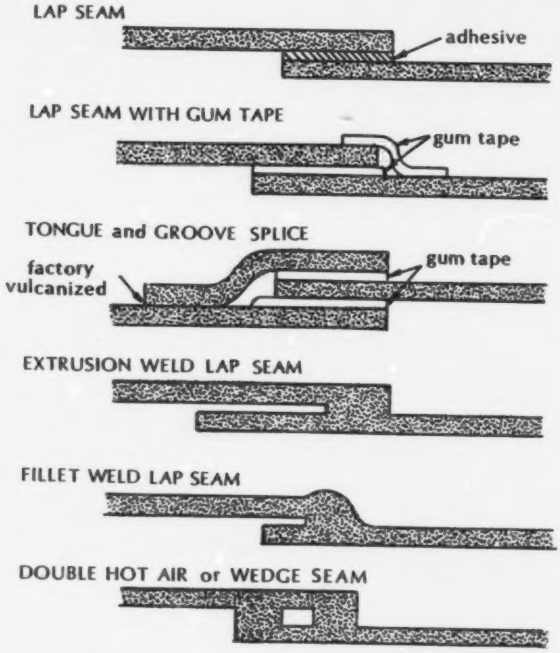


Figure 3.6 Configurations of Field Geomembrane Seams

Solvent-bonded seams depend on the ability of a solvent to dissolve the FML. The adhesive may be a bodied solvent adhesive, a solvent adhesive, or a contact adhesive. The bodied solvent uses 8 to 12% of the FML polymer dissolved in a volatile solvent. The solvent dissolves the surface of and softens the two sheets to be bonded and, with the application of pressure, enables a homogeneous bond. The solvent will evaporate with time leaving only the parent FML polymer. Solvent adhesives function like a bodied solvent but leave an adhesive that becomes an additional component in the FML. Contact adhesives differ from solvent adhesives in that significant pressure is not required to form a bond and the bond is instantaneous. Bonding methods using solvents and adhesives are normally used with FMLs composed of thermoplastics or thermoplastic elastomers.

Thermal methods can be used on most FML polymers except elastomers. These methods are preferred in most waste facility projects because no solvents are required. Thermal sealing uses forced air heated in excess of

260° C (500° F) to melt the two surfaces to be joined. The two surfaces are then rolled under pressure to force the two molten zones to flow together. Alternately, the two surfaces can be melted using an electrically heated wedge which is particularly good on thinner LLDPE and HDPE sheets. A third thermal method is the dielectric method that uses a high frequency electrical current to agitate the molecules within the FML to generate the heat required for a melt. In this country this method is, however, limited to use on thin liners and within a factory. Field dielectric seaming techniques are used in Europe.

Thermal extrusion welds are specialized thermal methods limited in application to thick HDPE liners. The specialized welders extrude a ribbon of molten HDPE that melts and then bonds to the two HDPE surfaces. The ribbon may be placed between the overlap and rolled to form a flat weld or it may be placed between two mating edges to form a fillet weld. Currently these are the most common seaming methods used in waste facility liners.

Vulcanized bonds are used on elastomers that will not go into solution with solvents and have poor thermal bonding properties. These bonds use an uncured tape formed of the polymer base with a cross-link agent. Under heat and pressure, the crosslink connects both elastomer surfaces to the ribbon to form a bond.

Recent work by Morrison (1986) on 37 combinations of supported and unsupported polymeric sheet materials was directed at evaluation of seam strengths over a 180-day period. Samples were exposed to 6 chemical solutions, brine and water immersion, freeze-thaw cycles, wet/dry cycling, heat aging, and accelerated outdoor aging. The results of the study indicated that there is no direct correlation between the seam strengths measured in shear and in peel. This study indicated that the shear strength is more indicative of the strength of the parent material, while the peel test is a good indicator of the strength of the seam. Both tests are reviewed in the appendices. This study also indicates that the factory seam requirements in NSF Standard No.54 are too low. The current requirement for unsupported materials such as CPE requires a film tearing bond of 10 pounds per inch. This is much less than can be easily obtained in the factory.

Currently there is no non-destructive field test for seam strength. While field seam testing is discussed in greater detail in Section V, it is helpful to review the two mechanical tests performed on samples cut from a field seam. The actions of the shear and peel tests are shown on Figure 3.7. The shear test simulates inservice stresses caused by thermal contraction of the membrane or tensile stresses being applied across adjacent sheets. Conventional acceptance criteria calls for the seam to be as strong as the parent liner material. Peggs (1985) suggests that for HDPE this may be improved by requiring that the failure stress exceeds 80% of the tensile yield stress of the base material. Additionally, Peggs suggests that the load elongation characteristics of the weld sample should be closely compared to that of the base material. Premature strain failure of the weld region may occur due to overheating of the seam during welding, excessive surface roughening during preparation of the panels, or from damage caused by accumulated dirt on the heated surfaces. Environmental stress rupture may be caused by underheating of the seam during welding due to stress cracking originating at the throat of the overlapped joint. The peel test evaluates the quality of fusion in the weld and does not

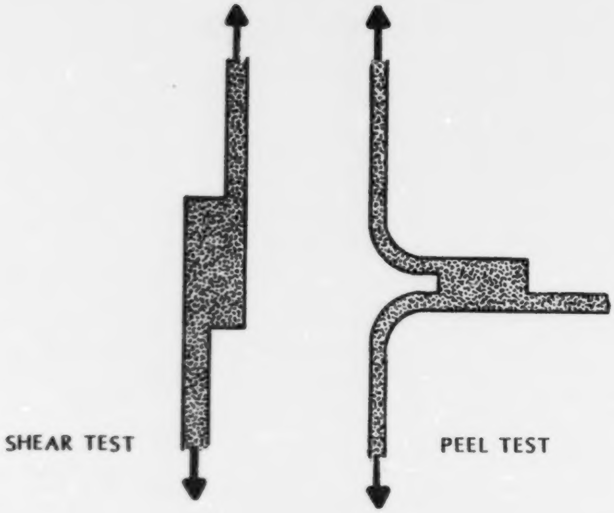


Figure 3.7 Seam Strength Tests

reproduce field loading conditions. Acceptance criteria for the peel test include failure occurring through the membrane, failure occurring outside the seam area, and if the peel strength exceeds 80% of the membrane yield stress. The results of the peel test are influenced by the thickness of the membrane, with the thicker membrane doing progressively poorer for a given quality of weld. The degradation with thickness is due to the increasing stiffness that introduces additional bending stresses to the seam.

A study of field construction and placement procedures by Shultz (1982) found that problems in the installation of polymeric liners include installation during marginal or adverse weather conditions, seaming around penetrations, and the field or laboratory inspection of field seams. Dry and warm field conditions are very important for proper seaming of polymeric liners. Minimum recommended temperature for proper field seaming is 15.5° C (60° F). While no maximum air humidity is specified for welding, certain combinations of humidity and FML temperature can cause moisture to condense on the surface of the FML. This moisture must be removed by preheating the FML prior to seaming. Seaming around penetrations and field inspection of FML seams is reviewed in Section V of this document.

FML Survivability

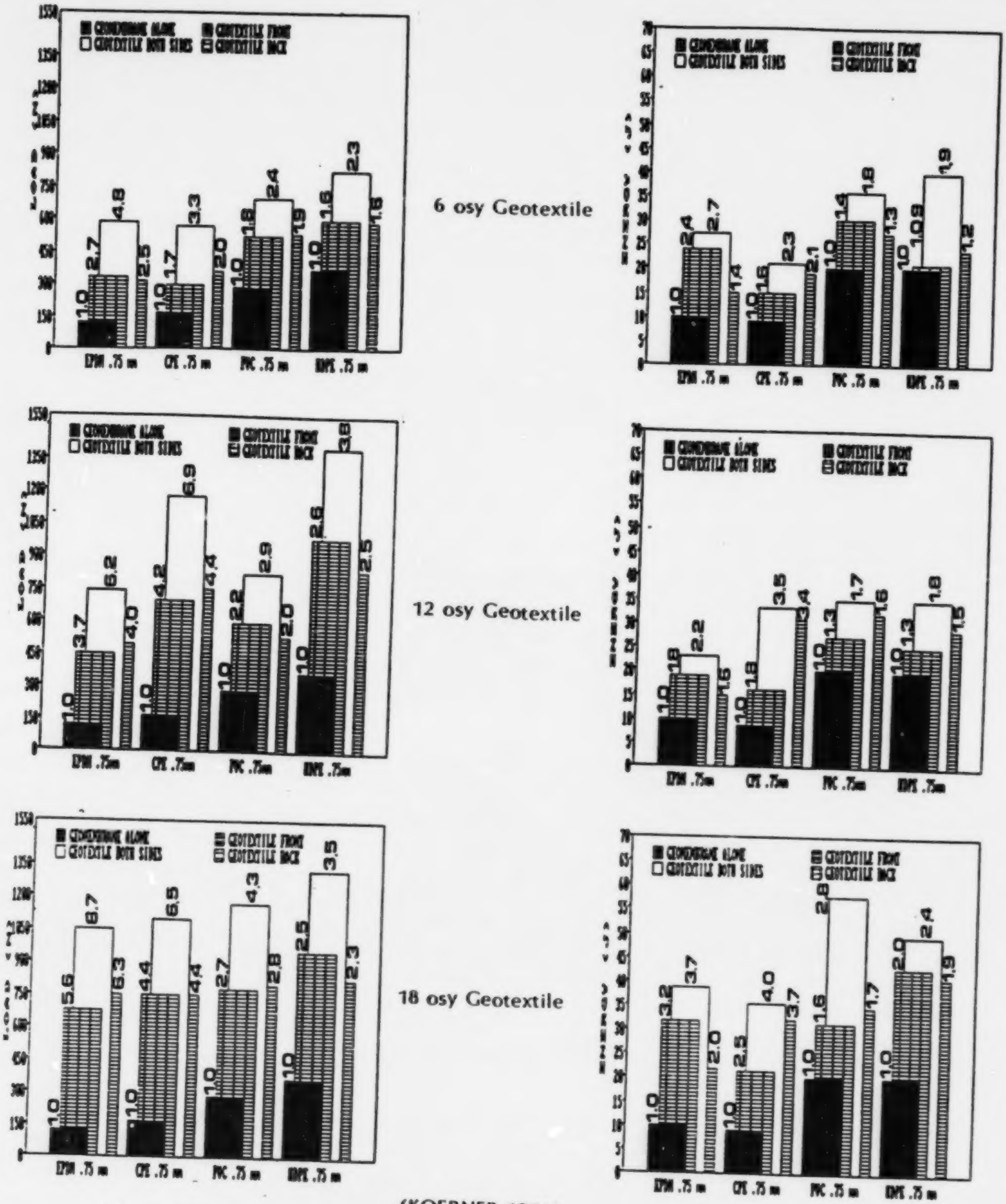
The ability of a flexible membrane liner to resist puncture and tear during installation and operation is critical. Puncture of a liner can occur due to falling objects, equipment moving on the liner, ice forces, abrasion and movement against sharp objects. Tearing is typically the result of a puncture being subjected to a tensile stress. In unreinforced membranes, the resistance to puncture at low deformation speeds and tear are a linear function of membrane thickness (Knipschild,1985,and Ainsworth,1984). Puncture of a membrane at high deformation rates, such as generated by falling objects, was shown by Knipschild (1985) to vary by the square of the membrane thickness. Ainsworth, however, reports a linear variation of puncture strength based on the Swiss Standard SIA 280/14. This test measures the critical drop height at which a standard bolt will not produce penetration of the membrane. The general improvement of performance with increased thickness is currently the basis for the use of membranes substantially in excess of the 30 mil statutory minimum thickness. Recalling Example 3.12, the FML thickness could be a fraction of the statute requirement based on purely hydraulic considerations. The thin membrane meeting hydraulic design guidelines would not, however, survive the installation process.

Puncture damage to an FML at low deformation rates can occur due to the presence of large rocks or sharp objects in the soil beneath or in the cover placed on top of the FML. This puncture resistance of a membrane is quantified using a simple laboratory test procedure that measures the ultimate force required to drive a 5/16 inch metal rod through the membrane, ASTM D3738. The puncture force indicated by the test is generally used as an index, with larger forces indicating a greater resistance to penetration. Minimum puncture resistance requirements are not established. However, the puncture resistance provided by the 30-mil statutory minimum thickness of HDPE is approximately 80 pounds. This must serve as an interim minimum design criteria.

Recent studies (Koerner,1986) have shown that the puncture resistance of an unreinforced membrane at both low and high deformation rates can be significantly increased by the addition of a geotextile behind the membrane, in front of it, or in both locations. The results of puncture tests on four 30 mil FMLs with and without a 12 oz./sq.yard non-woven geotextile are shown in Figure 3.8a. Proportional improvements were also measured using 6 and 18 ounce geotextiles. Current functional requirements for gas collection and monitoring of FML leakage require that a layer of sand or a synthetic drainage medium be placed beneath all FMLs. The effective puncture resistance of the FML will be greater than that of the FML alone. Puncture damage to an FML will be more likely to occur during the placement of cover soil on top of the FML. Puncture damage resulting from the placement of cover soils is caused by large rocks or sharp objects in the cover soil being driven through the membrane by large normal stresses from construction equipment during placement of the soil. Soil gradation requirements are used to minimize the occurrence of rocks within the cover soil. Typical cover soil gradation requirements are as follows:

U.S. Standard Sieve		Percent Passing (Range)
Sieve No.	Opening	
#4	4.76mm	100-90
#10	2.00	95-70
#20	0.84	80-50
#40	0.42	65-20
#100	0.149	40-10
#200	0.074	20- 5

In addition to gradation, a sufficient thickness of cover must be maintained to protect the FML from damage due to equipment loading. A complete discussion of construction criteria is given in Section V. The MTG recommends that each FML must be protected from damage from above and below by a minimum soil thickness of 30 centimeters (12 inches) nominal, 25 centimeters (10 inches) minimum, bedding material. The bedding material is to be no coarser than sand (USCS SP classification) with 100% of the



1 N = .225 lb.

(KOERNER, 1986)

1 J = .738 ft-lb

a. PUNCTURE RESISTANCE

b. IMPACT RESISTANCE

Figure 3.8 Survivability of Common FMLs

washed, rounded sand passing a 1/4-inch sieve. The material must be free of rock, fractured stone, debris, cobbles, rubbish, and roots.

Impact-type tests, ASTM E23, provide an alternate index of FML puncture resistance . The impact test provides an index of the ability of the FML to survive having cover material dropped directly on the FML. The ASTM test was developed for metals and is capable of very large impact energies. This test is currently under review by ASTM Committee D34 for use with geosynthetics. As with puncture, Koerner(1986) showed that the impact resistance of an FML increases almost linearly with thickness using the proposed ASTM test. Knipschield (1985), using the West German DIN 53 535 drop test observed an increase in puncture resistance that is proportional to the square of the thickness. Impact test data from the proposed ASTM test is shown on Figure 3.8b and generally indicates an increase in impact resistance with the addition of a geotextile. Note that there is no consistent agreement between impact and puncture data for a given polymer. In general, a polymer having good static puncture would also have good dynamic impact resistance. Both puncture tests show that a thinner FML can be used if it is protected by a geotextile. Current West German standards require a minimum penetration drop height of 0.75m using the DIN test procedure. While no correlation has been presented between the two tests, the West German minimum corresponds to a 1.4cm (40 mil) thickness of HDPE.

Table 3.1 Tear Resistance of FML (Koerner, 1986)

Polymer Composition	Reinforced	Thickness	Tear Resistance	
HDPE	No	40 mil	25-30 lbs	(1)
	No	80	60-70	(1)
	No	100	75-85	(1)
PVC	No	20 mil	6 lbs	(1)
	No	40	10	(1)
	No	50	14	(1)
CSPE	Yes	45 mil	25 lbs	(1)
	Yes	36	36	(2)

(1) ASTM D1004 (2) ASTM D751

In addition to puncture, a FML can be damaged by large tensile stresses that result in tearing. The tensile stresses during installation can be generated by dragging the FML during placement, and by wind-induced flapping of the FML. The tear resistance of a membrane is measured by typically using a notched specimen subjected to tensile forces that open the notch. Tear data for common unreinforced and reinforced polymers is shown in Table 3.1. The tear resistance of an unreinforced membrane increases with thickness of the membrane and is influenced by the polymer type. Tearing of a membrane requires an initial penetration, an applied tensile stress, and the ability to develop large strains. These conditions are only met during initial installation and can be minimized using the field installation procedures presented in Section V. Current West German standards require a minimum tear strength, DIN 53-455 , of 45 pounds.

A membrane must have sufficient modulus in addition to penetration and tear resistance. This ensures that excessive stretching of the FML will not occur and that local sheet deformations due to settlement will be resisted by a larger sheet area. West German standards require that the membrane support 89.9 pounds (40N) per 1.97 inches (50mm) width at less than 5% deformation, i.e. approximate modulus of 900 lb/in. Additionally, the West German standards require that the ultimate multi-axis strain determined from a burst test should be at least 10% at failure. Currently such multi-axis data is available (EPA,1983) only in the form of Mullen-burst test which is not suitable for membranes. A possible alternative is the large scale hydrostatic test reviewed in Appendix D.

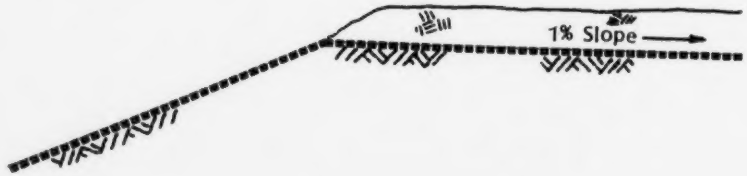
FML ANCHORAGE

The geotextiles and geomembranes lining the sides of waste facilities must be anchored at the top of these slopes to prevent movement of the systems into the cell. An anchor must provide sufficient restraint to prevent this movement but should not be so rigid or strong that the FML will tear before the anchor yields. The anchor should therefore be designed to provide a reaction force that is greater than that required to stabilize the synthetics and less than the ultimate strength of the attached components. Generally, the FML is anchored at the top of the berm using a (a) friction method, (b) trench and backfill method or (c) anchoring to a concrete structure, Figure 3.9. The trench and backfill technique is most often recommended by manufacturers, probably due to its simplicity and economy. Excavation of the anchor trench is accomplished by a trenching machine or by using a bulldozer blade tilted at an angle.

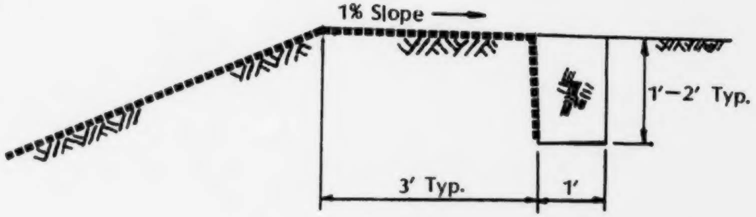
FML panels should be anchored following the field seaming operation. After the seaming crew has completed the seams for a particular panel, the panel should be anchored by backfilling the trench with soil or by anchoring the FML to the concrete structure. It is important that the panel not be anchored until it has been completely seamed to allow positioning as needed for optimum seaming. Anchoring the FML after seaming avoids stress tears on or along the seam from thermal contraction and expansion.

Anchor trench geometries include vertical walled trenchs, shallow "V" trenches, and horizontal embedment. Each trench geometry requires a different set of analysis assumptions. The vertical-walled trench requires the least amount of space but creates construction problems due to the vertical trench faces and greater difficulty in properly recompacting soil within the trench. Horizontal embedment requires the most land surface but makes the fewest analysis assumptions. Based on the accuracy of analysis assumptions, the three geometries can be ranked best to worst as horizontal, shallow "V", and vertical trench.

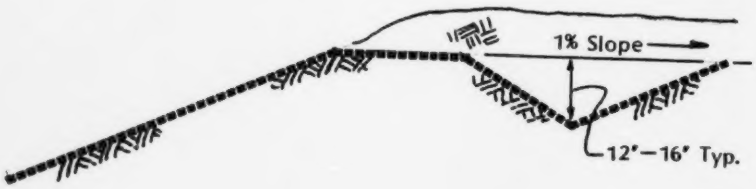
It should be noted that most anchor trenches are currently constructed to meet general recommendations provided by the FML installer. These recommendations are based on past experience and are purely empirical. No definitive field testing on actual anchorage capacities was found in the preparation of this study. In view of this lack of correlation between design capacities and actual field capacities, the designer is cautioned to compare design geometries with that recommended by the FML installer. When significant differences in proposed geometries exist, a limited field



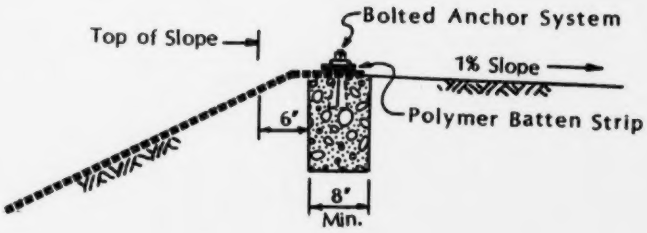
HORIZONTAL ANCHOR


1% Slope
1'–2' Typ.
3' Typ.
1'

TRENCH ANCHOR


1% Slope
12"–16" Typ.

SHALLOW "V" ANCHOR


Top of Slope
Bolted Anchor System
1% Slope
Polymer Batten Strip
6'
8"
Min.

CAST CONCRETE ANCHOR

Figure 3.9 FML ANCHORAGE DETAILS

pullout test should be performed to establish the actual ultimate force capacity of the anchor trench.

Both the shallow "V" and the horizontal embedment anchors rely exclusively on the frictional bond developed between the sheeting and the adjacent soil. Figure 3.10 shows the forces assumed and variables used in the analysis of these anchors. The pullout capacity, T, of horizontal and "V" anchors are given by

$$T_{horiz} = \frac{q\ L\ \tan\delta}{\cos\beta\ -\ \sin\beta\ \tan\delta} \qquad \text{Eq(3.19)}$$

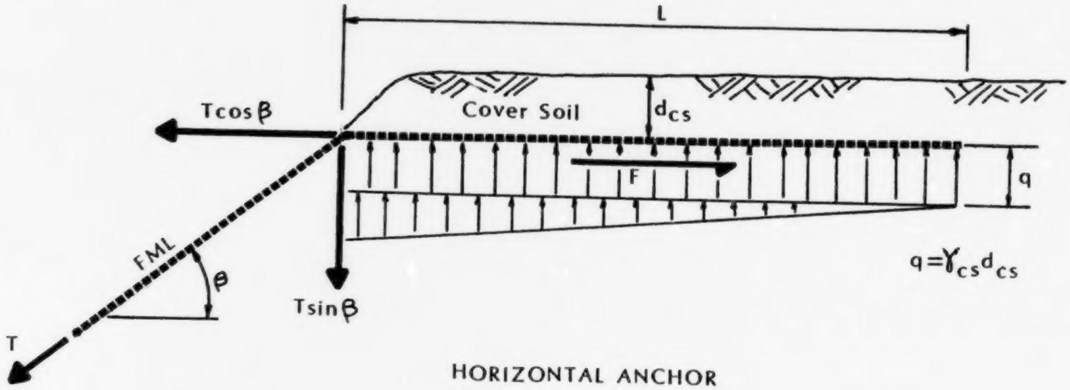
$$T_{"V"} = \frac{[q(L-L_V+L_V/\cos i) + (d_V L_V \gamma_{cs}/2\cos i)]\ \tan\delta}{\cos\beta\ -\ \sin\beta\ \tan\delta} \qquad \text{Eq(3.20)}$$

For deep waste cells, the runout length, L, required to develop sufficient frictional resistance may become excessive. Both frictional anchor concepts do, however, result in a significant simplification of analysis assumptions and a corresponding increase in confidence of the resulting calculated anchor capacity. Direct shear tests should be performed to establish the soil-geosynthetic friction angle, δ , used in these calculations.

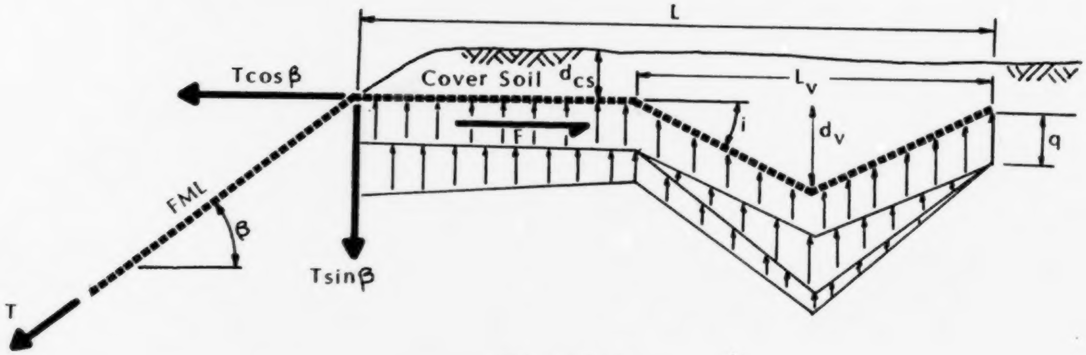
The analysis assumptions used in the vertical wall anchor trench are shown on Figure 3.10 for a trench anchor. The earth pressure assumptions made in the analysis were first proposed by Koerner(1986) and do not attempt to replicate the distribution of the actual field pressures but to estimate the total horizontal force component provided by the soil. The method sums forces in the horizontal plane to predict the anchor capacity. The most glaring assumption needed in this analysis is whether the embedded sheet will be stiff enough to produce a passive resistance force wedge. While appropriate for concrete anchors ,this assumption is poor for FML. The 90 degree entrant angle of the FML sheet into the trench produces a very difficult design condition. The tension forces in the horizontal sheet must be resisted by horizontal earth pressures from the soil adjacent to the sheet. Actual horizontal earth pressures during this process are largest at the surface and decrease to zero at some depth beneath the surface. Vertical force components resulting from the earth pressures at the ground surface and excess sheet tension may require pullout restraint obtained from further embedment of the sheeting below the point at which the horizontal earth pressure is zero. Unfortunately, no available analysis procedure correctly models the anchoring of an FML in a trench. It is reasonable to assume, however, that the earth pressure acting against the FML on the inside of the trench will be bounded by the passive and at-rest earth pressure assumptions. The anchorage capacity of the trench system can therefore be bounded using the following expression

$$T_{trench} = \frac{q\ L\ \tan\delta + (K'+K_a)\tan\ [0.5\ \gamma_{cs} d_{at}^2 + q d_{at}]}{\cos\beta\ -\sin\beta\ \tan\delta} \qquad \text{Eq(3.21)}$$

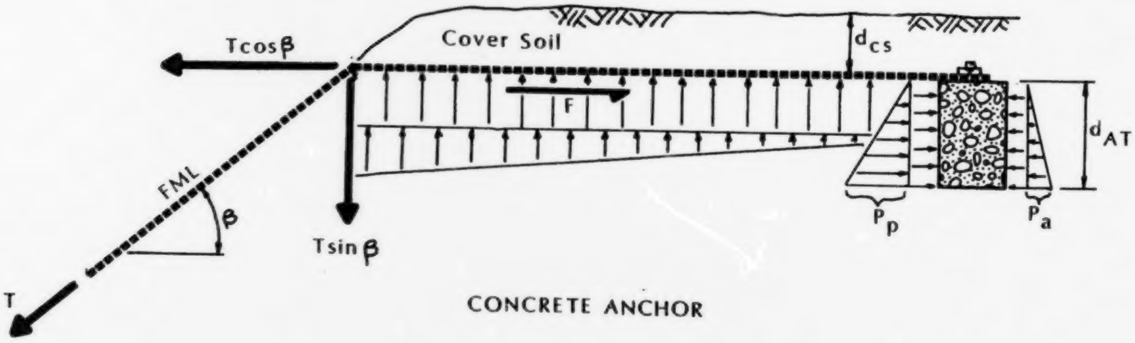
where K' is bounded by K_p and $K_{at\text{-}rest}$. For design it is recommended that


L
Tcos β
Cover Soil
d_{cs}
F
q
$q=\gamma_{cs}d_{cs}$
FML
β
Tsin β
T

HORIZONTAL ANCHOR


L
Tcos β
Cover Soil
d_{cs}
L_v
i
d_v
F
q
FML
β
Tsin β
T

'V' ANCHOR


Tcos β
Cover Soil
d_{cs}
F
d_{AT}
FML
β
Tsin β
P_p
P_a
T

CONCRETE ANCHOR

Figure 3.10 Forces and Variables - Anchor Analysis

the FML be sized so that it will not fail in tension if the full K_p pressure develops and T_{trench} calculated using $K_{at-rest}$ should exceed the pullout capacity to prevent failure in other modes.

The Design Ratio for the anchor should be low enough that the anchor will slip and prevent the FML or geotextile from tearing. An overly conservative design of the anchor may indeed lead to a needless tearing failure of the FML. Since the function served by the anchor is short lived, the designer can be justified in using a Design Ratio less than 2.0. An anchor design is shown on Example 3.17 using a vertical trench, horizontal, and a shallow "V" anchor trench.

The FML can also be anchored to concrete structures along the top of the berm by securing the geosynthetic with batten strips attached to anchor bolts embedded in the concrete. This technique is also applicable for bonding the FML to metal structures, such as pipes. A common approach entails placing the anchor bolts on 15 to 30 centimeter centers. The liner is placed over the bolts, an adhesive is generally applied to the FML, and the batten strip is secured and bolted in place. The analysis assumptions used in the vertical wall anchor trench are the same as shown on Figure 3.10 for a trench anchor. The anchor capacity is calculated using Eq(3.20) assuming K' is equal to K_p. Compatibility of the adhesive/sealant with the type of synthetic and liquid impounded must be verified to ensure the seal is maintained. Details of anchoring techniques are discussed by EPA (1984) and Kays (1977).

SURFACE IMPOUNDMENT CONSIDERATIONS

FML Protection

The liner system, including soil and flexible membrane components, plays a significant role in containing the wastes within the SI by preventing the migration and escape of hazardous waste and its constituents. To enhance the longevity of the liner, a protective covering will usually be required over the uppermost component to prevent damage from mechanical or environmental factors. The liner system will often have an FML as the uppermost component, which is sensitive to many of the following conditions (EPA, 1983):

1. Ultraviolet degradation of some polymers;
2. Infrared radiation;
3. Mechanical damage during placement of waste;
4. Wind;
5. Wave action;
6. Oxygen and ozone;
7. Freeze/thaw;
8. Hail/rain;
9. Animals; and
10. Vandalism.

A compacted soil liner is not as susceptible to these forces. However, a soil covering will provide additional protection from weathering effects which may change the properties or cause erosion of the liner. Weather effects include freeze/thaw, wave action or wind.

Protection of the FML is often provided by a soil cover of sufficient thickness to prevent mechanical damage from normal facility operations and maintenance equipment. In addition, the cover must withstand wind and wave action, and other environmental effects while remaining stable on the impoundment slope. EPA (1983) recommends a protective soil cover of at least 45 centimeters (18 inches) in thickness and a maximum side slope of 3 horizontal to 1 vertical based upon field experience. It also recommends the soil be placed at or near optimum moisture by light tracked vehicles to provide slight compaction of the material. This cover soil will be exposed to repeated wet-dry cycles and should therefore be primarily granular to prevent the development of soil cracking.

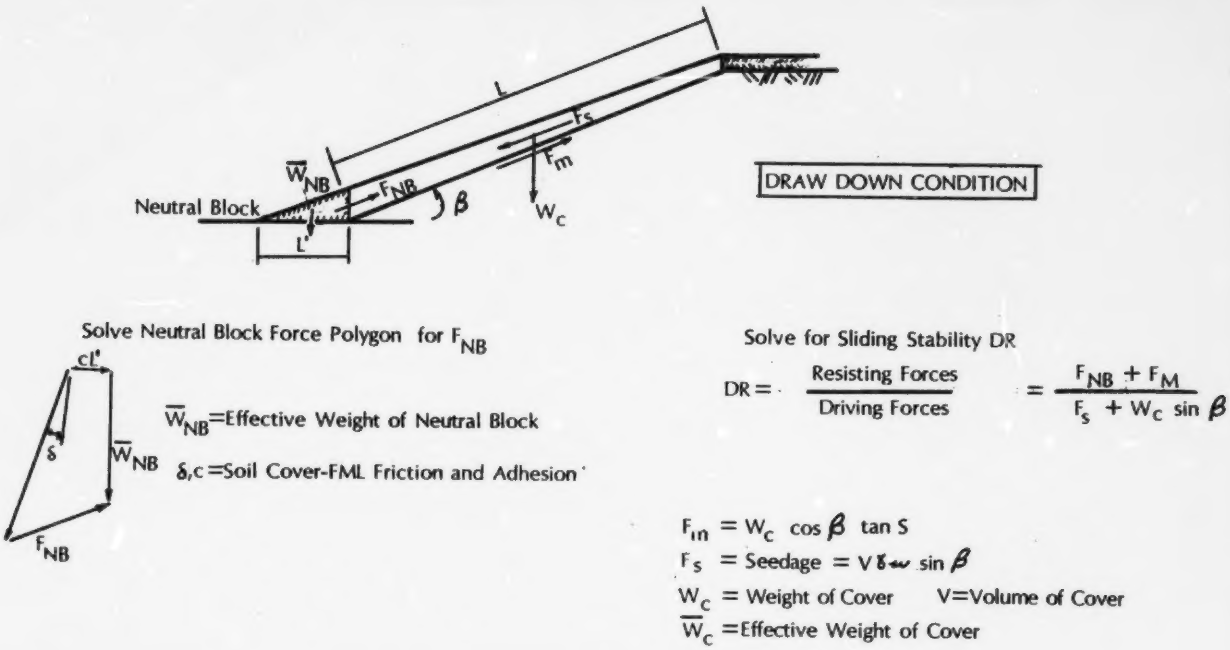
A critical condition in the soil cover exists if the liquid within the impoundment has saturated the cover soil and the liquid is then drained from the impoundment. The liquid draining from the cover soil exerts a seepage force that tends to push the soil cover downward. The design must first establish the internal stability of the soil cover layer itself, and then that of the soil layer on top of the FML. As the liquid within the reservoir is drawn down, excess pore water pressures within the primarily granular soil cover will dissipate and the liquid within the soil cover will flow parallel to the sideslope. Assuming the liquid within the cover is flowing parallel to the slope, the factor of safety, FS, against failure within the soil is given as (Lamb and Whitman, 1979)

$$FS = (1 - \gamma_w / \gamma_{sat}) (\tan \phi / \tan \alpha) \qquad Eq(3.22)$$

where γ_{sat} is the saturated unit weight of the soil, γ_w is the unit weight of water, ϕ is the effective internal angle of friction of the cover soil, and α is the slope of the cover soil. For typical values of γ_w, γ_{sat}, ϕ, and α, the resulting FS is always low and indicate potential failure by sloughing of the cover soil on the slope of the sidewalls.

If the liquid within the impoundment is drawn down instantaneously, then the initial flow of the fluid within the soil is horizontal. Excess hydrostatic pressures within the cover soil dissipate quickly and then the flow will be parallel to the slope. The initial condition of horizontal flow produces the larger flow forces (Giroud and Ah-Line,1984) but is only characteristic of a clayey soil cover or a catastrophic failure of the impoundment.

The stability of the soil cover on the FML is verified by summing the flow, gravitational, and anchorage forces parallel to the FML sideslope surface. The general analysis method is shown on Figure 3.11. For a typical granular cover, the soil-FML adhesion will be zero. If the cover soil contains an appreciable amount of clay, then the seepage force will act horizontal and be slightly larger than indicated above, see Giroud and Ah-Line, 1984. In addition to verifying stability, the calculations should be continued on to calculate the tension in the FML due to the cover soil and to verify the adequacy of the FML anchor and tensile strength. Design Example 3.18 demonstrate this analysis assuming the cover soil is a sand. Work by Mitchell and Gates, 1986, indicates that erosional considerations become significant if the sideslope is steeper than 20 degrees, or approximately a 3:1 slope.


L
F_s
F_m
$\overline{W}_{NB}$
F_{NB}
β
W_c
Neutral Block
L'
DRAW DOWN CONDITION
Solve Neutral Block Force Polygon for F_{NB}
cL'
δ
$\overline{W}_{NB}$
F_{NB}
$\overline{W}_{NB}$=Effective Weight of Neutral Block
δ,c =Soil Cover-FML Friction and Adhesion
Solve for Sliding Stability DR

$$DR = \frac{\text{Resisting Forces}}{\text{Driving Forces}} = \frac{F_{NB} + F_M}{F_s + W_c \sin\beta}$$

$F_m = W_c \cos\beta \tan S$

F_s = Seedage = $V \gamma_w \sin\beta$

W_c = Weight of Cover V=Volume of Cover

$\overline{W}_c$ =Effective Weight of Cover

Figure 3.11 Liner Cover Stability Analysis

Gas Venting

Surface impoundments or waste piles constructed using FML's must include provisions for removal of gases from beneath the membrane. These gases may be produced by underlying organic soils, leachate induced reactions, rising water table, or simply be air that is trapped in the facility during construction. If these gases are not removed, they may build up beneath the FML and eventually lift the FML to the surface of the contained fluid. These bubbles are commonly called 'whales' because of their physical appearance. Excessive stresses can be generated within the FML during formation of a whale and can lead to rupture of the FML. Gas collection is also a design consideration for the cap that covers the cell at closure and is discussed in Section V. The cap gas considerations are, however, concerned with gases generated within the cell and not those coming from the beneath the waste facility.

A recent study (EPA,1986a) indicates that no formal design procedures are available for gas drainage systems. The air transmissivity of geosynthetics has been studied and procedures are demonstrated in Section V for calculating the air flow capacity of an LCR system. However, an obvious problems in the design of such a system is the uncertainty associated in estimating the rate of gas generation. For conventional sanitary landfills, the rate of gas generation is estimated to range from 1.3 to 7.5 liters of gas per kilogram of waste per year (Emcon,1980). For the cap gas system in a hazardous waste landfill cell, even the lower value of this range is conservative. The rate of gas generation from beneath a given surface impoundment is not as easily bounded.

A number of guidelines have been developed for designing the gas venting system beneath FMLs. Kays (1977) recommends that the bottom slope of a facility that could experience gas generation from below the liner should have a minimum slope of 3%. Geosynthetic materials suitable for use as gas vents are as (Giroud and Bonaparte,1984) follows:

a. Needle-punched, nonwoven fabrics having a thickness from 80 to 200 mils
b. Mats (3/8 to 3/4 inch thick)
c. Nets or grids (approximately 1/4 inch thick)
d. Corrugated, or waffled plates (3/8 to 3/4 inch thick) covered with fabric

These dimensions closely correspond to the geosynthetic materials that are currently being used to fabricate LCR systems. Thus it is anticipated that a properly designed LCR system will provide a good beginning for a gas venting system. Operationally, it is not uncommon for passive gas collector systems to be converted to active systems with the addition of fans. The active system can move significantly larger volumes of gas.

The gas venting system will require additional design considerations beyond that required for the LCR system. Beyond increasing the bottom slope from 2% to 3%, the designer must provide sufficient gas vents high on the side slopes just below the top of the berm. The vent spacing may vary, but a minimum vent spacing of 50 ft. is recommended. Typical gas vent details are shown on Figure 3.12. These vents function just like those that vent the plumbing system in a conventional house. Gas is allowed to leave the system, yet rainfall and surface water is prevented from flowing into the system.

Past problems with gas venting systems beneath surface impoundments include failures caused by water collecting in the gas venting system and either reducing the effectiveness of the vent or creating high water pressures that eventually lifted the FML above the surface of the liquid being contained. Under draft MTG (EPA,1985) an LCR would be under the FMLs and would act as a gas venting system. Water entering this system due to a failure of the gas vents would be removed as leachate and not allowed to build up beneath the system. This additional water would add expense to the operator to dispose of or treat, however.

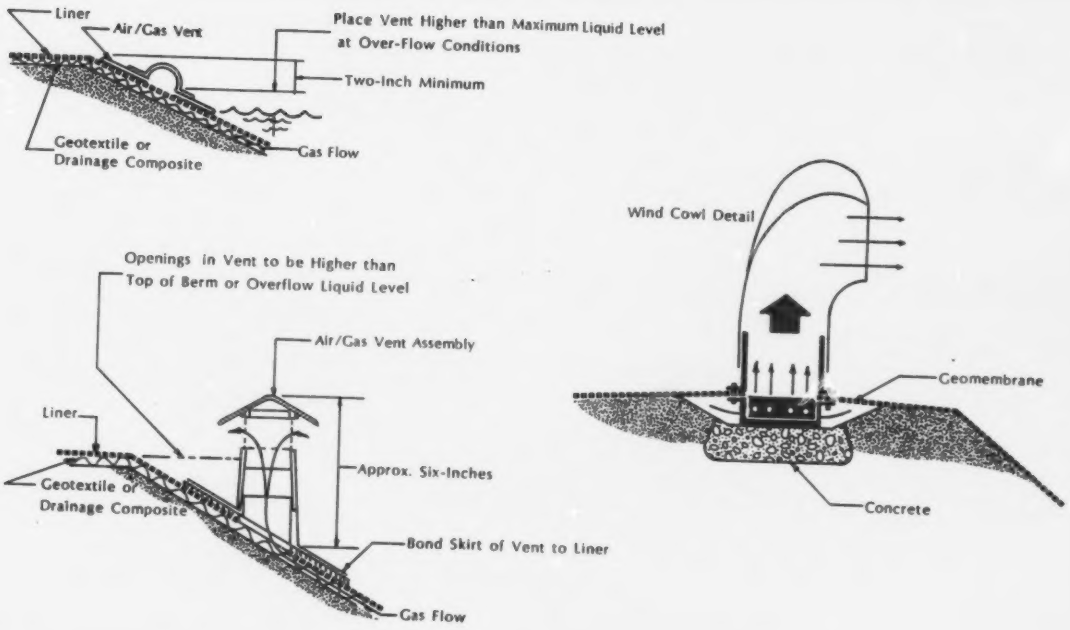

Liner
Air/Gas Vent
Place Vent Higher than Maximum Liquid Level at Over-Flow Conditions
Two-Inch Minimum
Geotextile or Drainage Composite
Gas Flow
Wind Cowl Detail
Openings in Vent to be Higher than Top of Berm or Overflow Liquid Level
Air/Gas Vent Assembly
Liner
Geotextile or Drainage Composite
Approx. Six-Inches
Bond Skirt of Vent to Liner
Gas Flow
Geomembrane
Concrete

Figure 3.12 Typical Gas Vent Details

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Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEMS

Consideration: TRANSMISSIVITY, VERIFY THAT LCR PROVIDES ADEQUATE PLANAR FLOW.

Required Material Properties	Range	Test	Standard
PLANAR FLOW CAPACITY	3×10^{-5}* (m^2/s)	TRANSMISSIVITY	ASTM D4617

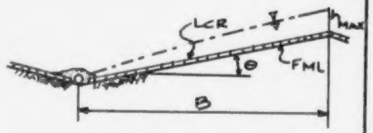
*Draft MTG Minimum

Analysis Procedure:

(1) DEFINE MINIMUM TRANSMISSIVITY

- STATUTORY - $3 \times 10^{-5}\ m^2/s$
- 1-FOOT HEAD

$$T = \frac{B^2 * q}{h_{max} + B \sin\theta}$$



q = LEACHATE INFLOW RATE

h_{max} = 1 FOOT OF HEAD

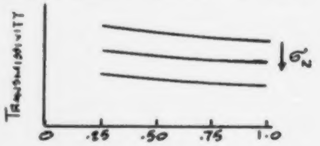
(2) CALCULATE MAXIMUM NORMAL STRESS

$$\sigma_N = D * \gamma$$

D = FINAL DEPTH CAP TO LCR

γ = UNIT WEIGHT OF FILL

(3) OBTAIN LABORATORY TRANSMISSIVITY DATA



FIELD GRADIENT, i

$$i = \Delta h/L = \frac{h_{max} + B \sin\theta}{(B/\cos\theta)}$$

(4) DEFINE DESIGN RATIO

$$DR = \frac{T_{LCR}}{T_{REQUIRED}}$$

Design Ratio:

$DR_{min} = 10$ DUE TO COMPRESSIVE CREEP IN SYNTHETIC LCR

References:

DEMETRACOPOULOS (1984)
WONG (1977)
SCHARCH (1981)

Example:

GIVEN:

- LANDFILL HT, D = 120'
- UNIT WT. WASTE, γ = 80 lb/ft³
- SLOPE ANGLE, θ = 4°
- SLOPE LENGTH, B = 60'
- LEACHATE INFLOW RATE, q = 0.01 FT/DAY
- LABORATORY TRANSMISSIVITY DATA

(1) DEFINE MINIMUM TRANSMISSIVITY (FLOW CRITERIA)

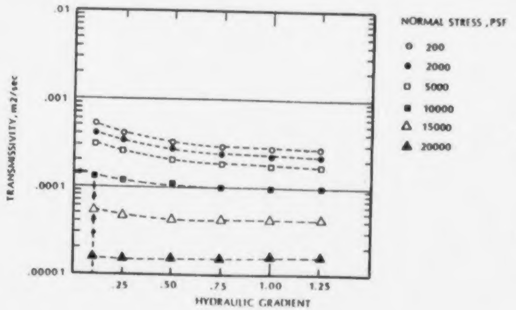
$$T = \frac{60^2 * 0.01}{1 + 60 \sin 4^\circ} = 6.94\ FT^2/DAY = 7.46 \times 10^{-6}\ m^2/SEC$$

$$\therefore T_{REQ} = \underline{7.46 \times 10^{-6}\ m^2/s}\ (> 3 \times 10^{-5}\ m^2/s)$$

(2) CALCULATE MAXIMUM NORMAL STRESS, σ_N

$$\sigma_N = 120 \times 80 = 9600\ PSF$$

(3) OBTAIN LCR TRANSMISSIVITY FROM LAB. DATA, T_{LCR}



$$GRADIENT,\ i = \frac{1 + 60 \sin 4^\circ}{(60/\cos 4^\circ)}$$

$$\underline{\underline{i = .086}}$$

$$T_{LCR} = \underline{\underline{.00014\ m^2/s}}$$

(4) CALCULATE DESIGN RATIOS

$$DR_{FLOW} = \frac{T_{LCR}}{T_{REQ.}} = \frac{.00014}{7.46 \times 10^{-6}} = 18.8 \quad \underline{OK}$$

$$DR_{MTG} = \frac{T_{LCR}}{T_{MTG}} = \frac{.00014}{3 \times 10^{-5}} = 4.67 \quad \underline{MARGINAL}$$

Example No. 3.1

Cell Component: LEACHATE COLLECTION REMOVAL SYSTEM

Consideration: TRANSMISSIVITY: OPERATIONS, VERIFY THAT PRIMARY LCR WILL HANDLE SURFACE WATER DURING OPERATION OF THE FACILITY

Required Material Properties	Range	Test	Standard
PLANAL FLOW CAPACITY	10^{-3} M²/S*	TRANSMISSIVITY	ASTM 4617

*Draft MTG Minimum

Anaiysis Procedure:

(1) CALCULATE RUNOFF VOLUME (REF EPA, 1986a)

$Q = C\,I\,A$ WHERE $C \approx 1.0$

$Q = FT^3/SECOND$

I = AVERAGE RAINFALL INTENSITY, IN/HR

A = WATERSHED AREA, ACRE

(2) CONVERT RUNOFF VOLUME TO Q/FT ENTERING LCR

$q = Q / (\text{LENGTH OF EFFECTIVE LCR}) = CU\,FT/SEC/FT$

(3) CALCULATE REQUIRED TRANSMISSIVITY

REWRITING EQ 3.4 $\theta_{REQ} = q\left[\frac{L}{dh}\right] W$

WHERE L = FLOW LENGTH

Δh = HEAD LOSS

W = WIDTH OF LCR

(4) CALCULATE DESIGN RATIO

$DR = \dfrac{\theta_{ACT}}{\theta_{REQ}}$

Design Ratio: $DR_{MIN} = 3.0$

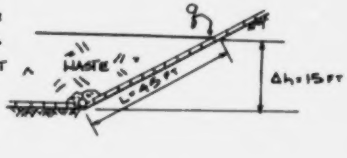
LOWER DR REFLECTS PROBABILITY THAT THE DESIGN EVENT WILL NOT OCCUR DURING OPERATION OF FACILITY

References:

Example:

GIVEN:

- RAINFALL INTENSITY, I = 4.0 IN/HR
- WATERSHED AREA, A = 2.5 ACRES
- LCR PERIMETER TO WATERSHED = 160 FT
- Δh = 15', ΔL = 45 FT



(1) CALCULATE RUNOFF VOLUME

$Q = 1 \times 4 \times 2.5 = \underline{\underline{10.0}}\ FT^3/SECOND$

(2) CONVERT Q TO Q/FT ENTERING LCR

$q = 10.0/160 = \underline{\underline{.0625}}\ FT^3/SEC/FT$

(3) CALCULATE REQUIRED TRANSMISSIVITY

$\theta_{REQ} = .0625 * \frac{45}{15} * 1$

$\theta_{REQ} = 0.1875\ FT^2/SEC$ $(9.29 \times 10^{-2}\ M^2/FT^2)$

$\theta_{REQ} = \underline{\underline{0.0174\ M^2/SEC}}$

(4) CALCULATE DESIGN RATIO

·OBTAIN ACTUAL θ W/ $i = \frac{15}{45} = .33$ AND $\sigma_N = 15 \times 80 = 1200\ PSF$

[E.G. SEE EX 3.1 ➔ $\theta_{ACT} = .006\ M^2/SEC$]

$DR = \dfrac{.006}{.017} = 0.35$ N.G.

∴ INCREASE θ OR DECREASE WATERSHED AREA

Example No. 3.2

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEMS

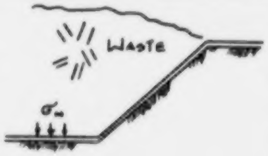
Consideration: TRANSMISSIVITY: CREEP, DETERMINE LONG-TERM CREEP IMPACT ON TRANSMISSIVITY OF SYNTHETIC LCR

Required Material Properties	Range	Test	Standard
LONG-TERM PLANAR FLOW CAPACITY	3×10^{-5} * (MIN) (M^2/SEC)	TRANSMISSIVITY	ASTM D4617

* Draft MTG Minimum

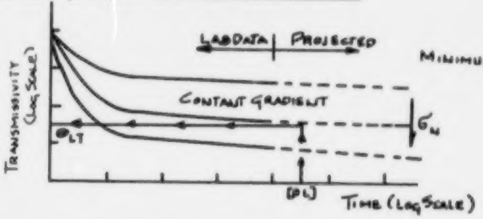
Analysis Procedure:

(1) CALCULATE MAXIMUM NORMAL STRESS, σ_N



$\sigma_N = \gamma \cdot D$ γ = UNIT WT. TRASH
D = DEPTH TO LCR

(2) OBTAIN LONG TERM TRANSMISSIVITY DATA



MINIMUM DESIGN LIFE = 50 YEAR

(3) PROJECT LONG-TERM TRANSMISSIVITY, θ_{LT}

θ_{LT} = OBTAIN FROM GRAPHICAL PROJECTION

(4) CALCULATE DESIGN RATIO, DR

$$DR = \frac{\theta_{LT}}{\theta_{REQ}}$$

Design Ratio:

$DR_{MIN} = 5.0$ REDUCED FROM EX. 3.1 SINCE CREEP IS NOW INCLUDED.

References:

Example:

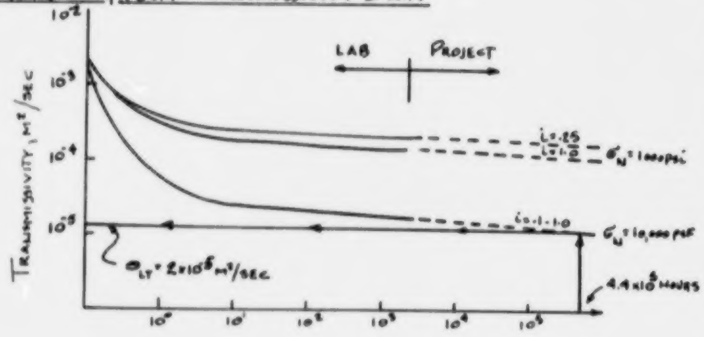
GIVEN:

- LANDFILL HT. = 120'
- UNIT WT. WASTE = 80 lb/ft³
- DESIGN LIFETIME = 50 YEAR = $.44 \times 10^6$ HOURS
- FIELD GRADIENT, i = .086 (REF EX. 3.1)

(1) CALCULATE MAXIMUM NORMAL STRESS, σ_N

$\sigma_N = 80 \times 120 = 9600$ lb/ft²

(2) OBTAIN LONG-TERM TRANSMISSIVITY DATA



(3) PROJECT LONG TERM TRANSMISSIVITY

FROM CHART $\theta_{LT} = 1.5 \times 10^{-5}$ M²/SEC

(4) CALCULATE DESIGN RATIO

$$DR = \frac{1.5 \times 10^{-5}}{3 \times 10^{-5}} = .5$$

NG

ASSUMING $\theta_{REQ} = \theta_{MTG}$

Example No. 3.3

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

Consideration: PERMITIVITY, VERIFY THAT A GEOTEXTILE WILL ALLOW LEACHATE TO FLOW THROUGH IT.

Required Material Properties	Range	Test	Standard
FLOW NORMAL TO GEOTEXTILE Draft MTG Minimum	0.5 TO 0.005 (sec^{-1})	PERMITIVITY	ASTM D4491

Analysis Procedure:

(1) CALCULATE REQUIRED PERMITIVITY, Ψ_{REQ}

$$q = K i A \qquad \text{(DARCY'S EQUATION)}$$

$$q = K \frac{\Delta h}{t} A$$

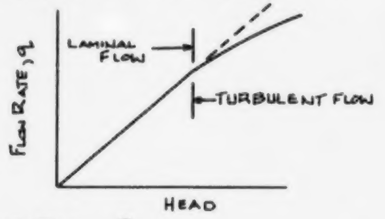
Δh = MAX. 1 FT HEAD

A = UNIT AREA

$$\frac{K}{t} = \Psi_{REQ} = \frac{q}{\Delta h A}$$

(2) OBTAIN GEOTEXTILE PERMITIVITY, Ψ_{GEO}

RESULTS PER ASTM D4491



$$\Psi_{GEO} = \frac{q R_t}{h A}$$

R_t = TEMP CORRECTION

h = HEAD

A = AREA OF TEST

(3) CALCULATE DESIGN RATIO

$$DR = \frac{\Psi_{GEO}}{\Psi_{REQ}}$$

Design Ratio:

DR > 50

References:

Example:

GIVEN:

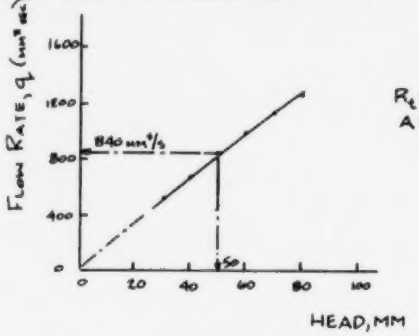
- LEACHATE INFLOW RATE, $q = 0.01$ FT/DAY
- MAXIMUM HEAD = 1 FT (MTG DRAFT)

(1) CALCULATE REQUIRED PERMITIVITY, Ψ_{REQ}

$$\Psi_{REQ} = \frac{0.01}{1 \times 1} \qquad \text{ASSUME UNIT AREA}$$

$$= 0.01\ DAY^{-1} = \underline{\underline{1.16 \times 10^{-6}}}\ SEC^{-1}$$

(2) OBTAIN GEOTEXTILE PERMITIVITY, Ψ_{GEO}



$R_t = 1.0$

$A = \frac{\pi}{4} \times 73\,mm^2 = 4185\,mm^2$

$$\Psi_{GEO} = \frac{840 \times 1}{50 \times 4185} = \underline{\underline{4 \times 10^{-3}\ SEC^{-1}}}$$

(3) CALCULATE DESIGN RATIO

$$DR = \frac{4 \times 10^{-3}}{1.16 \times 10^{-6}} = \underline{\underline{3460}}$$

Example No. 3.4

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

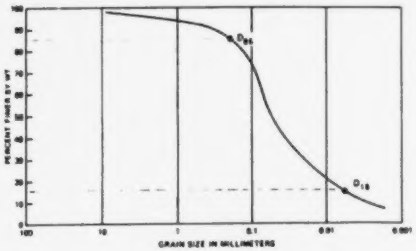
Consideration: FILTER-RETENTION, COMPARE GRAIN SIZE DISTRIBUTION OF RETAINED SOIL TO OPENING SIZE OF GEOTEXTILE TO VERIFY RETENTION OF PARTICLES.

Required Material Properties	Range	Test	Standard
APPARANT OPENING SIZE	2.00 TO 0.074 (MM)	AOS	CHO 2215 PROPOSED ASTM

Draft MTG Minimum

Analysis Procedure:

(1) OBTAIN PARTICLE SIZE OF COVER SOIL TO BE RETAINED (ASTM D422)



U.S. Standard Sieve No.	Sieve Opening (mm)
4	4.75
10	2.00
20	0.85
40	0.425
60	0.25
100	0.15
140	0.106
200	0.075

CU = COEFFICIENT UNIFORMITY $= D_{60}/D_{10}$

(2) OBTAIN AOS FOR GEOTEXTILE

AOS IS DEFINED AS THE SIZE OF UNIFORM GLASS BEAD FOR WHICH 5% OR LESS PASS THROUGH THE FABRIC. AOS $\equiv O_{95}$ (SEE APPENDIX)

(3) EVALUATE FILTER CRITERIA

REF. PGS III-7 - III-8

Design Ratio:

NOT APPLICABLE

References:

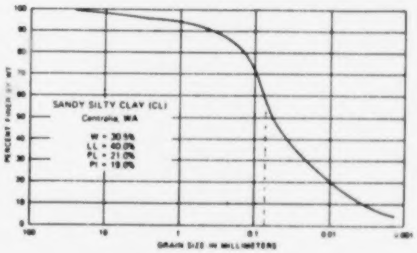
- GIROUD (1984)
- CARROLL (1979), CHEN (1981)
- TASK FORCE 25 (1983)

Example:

GIVEN:

- AOS OF GEOTEXTILE = #60 SIEVE (0.25 MM)

(1) OBTAIN PARTICLE SIZE OF SOIL TO BE RETAINED



$D_{85} = 0.54$ mm
$D_{60} = 0.075$ mm
$D_{15} = 0.009$ mm
$D_{10} = 0.0074$ mm

$CU = D_{60}/D_{10} = \underline{10.1}$

(2) OBTAIN AOS FOR GEOTEXTILE

AOS $= O_{95}$ GIVEN AS 0.25 MM (#60)

(3) EVALUATE FILTER CRITERIA

TASK FORCE 25 : FROM GRAPH 60% PASSING #200

$\rightarrow$ O_{95} REQUIRED = #50 < #60 $\underline{\text{OK}}$

CARROLL/CHEN : $O_{95}/D_{85} = .25/0.54 = 0.46 < 2$ $\underline{\text{OK}}$

$O_{95}/D_{15} = .25/0.009 = 27.7 > 2$ $\underline{\text{OK}}$

GIROUD: (ASSUME INTERMEDIATE DENSITY)

$CU = 10.1 \rightarrow O_{95} < (13.5 D_{50})/CU$ $D_{50} = 0.089$

$.25 < (13.5 * 0.089)/10.1$
$.25 < 0.12$ $\underline{\text{OK}}$

Example No. 3.5

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEMS

Consideration: FILTER-CLOGGING; EVALUATE THE INFLUENCE OF RETAINED SOIL PARTICLES ON THE PERMITIVITY OF A GEOTEXTILE.

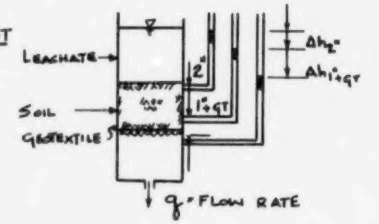
Required Material Properties	Range	Test	Standard
DIRECT MEASURE OF CLOGGING POTENTIAL Draft MTG Minimum	.1 TO 30	GRADIENT RATIO	PROPOSED ASTM

Analysis Procedure:

(1) PERFORM GRADIENT RATIO TEST

$$GR \equiv \frac{\Delta h_{1''+GT} / \Delta S_{1''+GT}}{\Delta h_{2''} / \Delta S_{2''}}$$

ΔS = THICKNESS, INCH

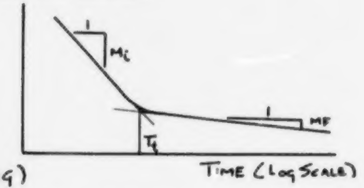


(2) EVALUATE GRADIENT RATIO

GR > 3 NG

(3) OPTIONAL LONG-TERM FLOW TEST

M_i = INITIAL SLOPE
T_t = TRANSITION TIME
M_F = FINAL SLOPE
= 0 (OK)
= SLIGHTLY NEGATIVE (?)
= STRONGLY NEGATIVE (NG)



Design Ratio:

NOT APPLICABLE

References:

- CALHOUN (1972)
- KOERNER AND KO (1982)

Example:

GIVEN:

- SOIL SAMPLE FROM SPECIFIC SITE
- SPECIFIC GEOTEXTILE TO EVALUATE

(1) PERFORM GRADIENT RATIO TEST

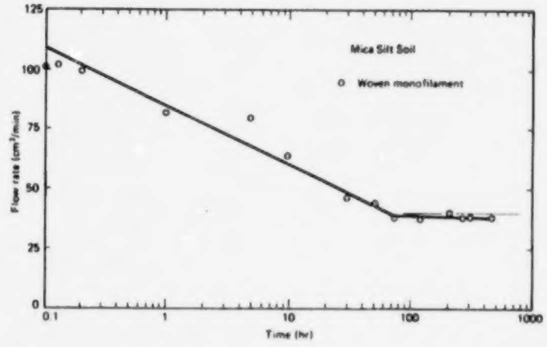
$\Delta h_{2''} = 3.6''$
$\Delta h_{1''+GT} = 5.7''$
$\Delta S_{2''} = 2.0''$
$\Delta S_{1''+GT} = 1.015''$

$$GR = \frac{3.6/1.015}{5.7/2.0} = \frac{3.54}{2.85} = \underline{\underline{1.24}}$$

(2) EVALUATE GRADIENT RATIO

GR = 1.24 < 3.0 OK

(3) OPTIONAL LONG-TERM FLOW TEST



M_F = SLIGHTLY NEGATIVE

∴ GEOTEXTILE MAY SUFFER CLOGGING WITH TIME

Example No. 3.6

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

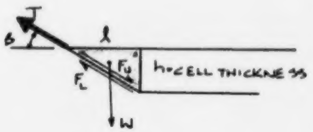
Consideration: STRENGTH-SLIDING; EVALUATE STRESSES GENERATED DURING CONSTRUCTION OF INTERIOR CELLS ADJACENT TO SIDE WALLS OF FACILITY.

Required Material Properties	Range	Test	Standard
FRICTION ANGLES			
• LCR-TO-WASTE, δ_U	20° - 45°	DIRECT SHEAR	ASTM
• LCR-TO-FML, δ_L	10° - 30°	" "	(TENTATIVE)
TENSILE STRENGTH OF LCR		WIDE-WIDTH TENSILE	ASTM D 4595

Draft MTG Minimum

Analysis Procedure:

(1) EVALUATE TENSION IN LCR



$T = F_U - F_L$

WHERE

$F_U = W \cos\beta \tan\delta_u$ δ=FRICTION ANGLES

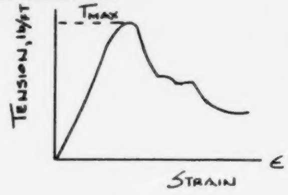
$F_L = W \cos\beta \tan\delta_L$

$W = \frac{1}{2}(h\ell)\gamma$ γ=UNIT WT. OF WASTE

(2) OBTAIN LABORATORY TENSILE STRENGTH

USING 4"-8" WIDE SAMPLE

→ T_{MAX}



(3) CALCULATE DESIGN RATIO

$$DR = \frac{T_{MAX}}{T}$$

Design Ratio:

$DR_{MIN} = 3.0$

References:

Example:

GIVEN:

- CELL THICKNESS, h=5'
- UNIT WT. WASTE, γ=80 PCF
- SLOPE ANGLE, β=30°
- FRICTION ANGLES
  - + LCR-TO-WASTE, $\delta_U = 40°$
  - + LCR-TO-FML, $\delta_L = 25°$

(1) EVALUATE TENSION IN LCR

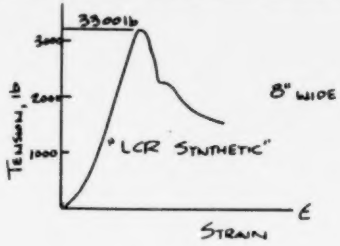
$W = \frac{1}{2}(h\ell)\gamma = \frac{1}{2}(5\times(5/\tan 30°))80 = 1732$ lb/FT

$F_U = 1732 \times \cos 30° \times \tan 40° = 1258$ lb/FT

$F_L = 1732 \times \cos 30° \times \tan 25° = 699$ lb/FT

$T = 1258 - 699 = \underline{\underline{559}}$ lb/FT

(2) OBTAIN LABORATORY TENSILE STRENGTH



8" WIDE SAMPLE → T = $\underline{\underline{4950}}$ lb/FT

(3) CALCULATE DESIGN RATIO

$DR = \frac{4950}{559} = 8.8$ OK

Example No. 3.7

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

Consideration: STRENGTH-SETTLEMENT ; DETERMINE ABILITY OF LCR TO RESIST DOWN-DRAG FORCES RESULTING FROM THE SUBSIDENCE OF THE CONTAINED WASTE

Required Material Properties		Range	Test	Standard
FRICTION ANGLE	LCR-TO-WASTE	20°-45°	DIRECT SHEAR	ASTM (TENTATIVE)
	LCR-TO-FML	10°-30°		
TENSILE STRENGTH OF LCR			WIDE WIDTH	ASTM D4595

Draft MTG Minimum

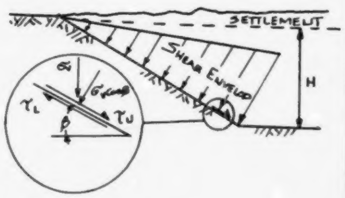
Analysis Procedure:

(1) EVALUATE TENSION IN LCR

$$\text{TOTAL SHEAR} = \tfrac{1}{2}\gamma H^2 \cos\beta \left[\frac{\tan\delta_U - \tan\delta_L}{\tan\beta}\right]$$

WHERE

γ = UNIT WT. WASTE
H = DEPTH OF WASTE
β = SLOPE ANGLE
δ_U = LCR-TO-WASTE FRICTION ANGLE
δ_L = LCR-TO-FML FRICTION ANGLE



(2) OBTAIN LABORATORY TENSILE STRENGTH

SEE EXAMPLE 3.7

(3) CALCULATE DESIGN RATIO

$$DR = \frac{T_{MAX}}{\text{TOTAL SHEAR}/FT}$$

Design Ratio:
ANALYSIS METHOD NOT RECOMMENDED

References:

Example:

GIVEN:

- WASTE HEIGHT, H = 120 FT
- UNIT WT. WASTE, γ = 80 PCF
- SLOPE ANGLE, β = 30°
- FRICTION ANGLES δ_U = 20°, δ_L = 15°

(1) CALCULATE TENSION IN LCR

TOTAL SHEAR / FOOT

$$T_L = \tfrac{1}{2}\, 80 \times 120^2 \cos 30^\circ \left[\frac{\tan 20^\circ - \tan 15^\circ}{\tan 30^\circ}\right]$$

$$T_L = \underline{82{,}960 \text{ lbs/FT}}$$

(2) OBTAIN LABORATORY TENSILE STRENGTH

SEE EXAMPLE 3.7

$$T = 4950 \text{ lb/FT}$$

(3) CALCULATE DESIGN RATIO

$$DR = \frac{4950}{82{,}960} = \underset{\sim}{0.05} \qquad \underset{\sim}{NG}$$

RECOMMEND: PERFORM ANALYSIS USING STRAIN COMPATIBILITY, EXAMPLE 3.9

Example No. 3.8

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

Consideration: STRAIN-SETTLEMENT; EVALUATE STRAINS PRODUCED IN LCR BY SETTLEMENT OF WASTE.

Required Material Properties	Range	Test	Standard
LOAD-ELONGATION CURVE FOR LCR		TENSILE TEST	ASTM D4595

Draft MTG Minimum

Analysis Procedure:

(1) ESTIMATE SIDEWALL SETTLEMENT OF WASTE

ASSUME $\Delta_{ss} = \Delta_{MAX} * \sin\beta$

Δ_{ss} = SETTLEMENT @ SIDESLOPE

Δ_{MAX} = MAX. WASTE SETTLEMENT

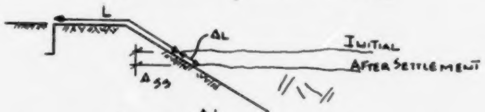
β = SLOPE OF SIDESLOPE

(2) OBTAIN LABORATORY LOAD-ELONGATION DATA

SEE EXAMPLE 3.7 → ϵ_{YIELD}, $\epsilon_{ULTIMATE}$ ϵ = STRAIN

(3) ESTIMATE MAXIMUM STRAIN IN LCR DUE TO SETTLEMENT

- ASSUME LCR FOLLOWS WASTE



$$\epsilon_{SETT} = \frac{\Delta L}{L}$$

(4) CALCULATE DESIGN RATIO

$$DR_{YIELD} = \frac{\epsilon_{YIELD}}{\epsilon_{SETT}} \qquad DR_{ULT} = \frac{\epsilon_{ULT}}{\epsilon_{SETT}}$$

Design Ratio:

$DR_{YIELD} > 0.5$

DR_{ULT} = 1.5 MIN

References:

Example:

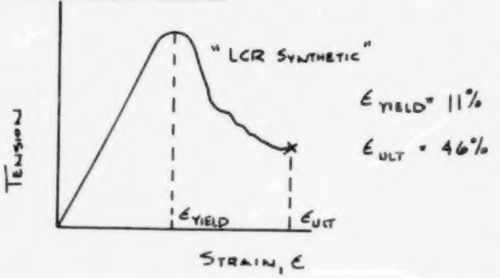
GIVEN:

- SLOPE ANGLE = β = 20°
- Δ_{MAX} = 18 INCHES

(1) ESTIMATE SIDEWALL SETTLEMENT, Δ_{ss}

$\Delta_{ss} = \Delta_{MAX} \sin\beta = 18 \times \sin 20° = 6.2$ INCHES

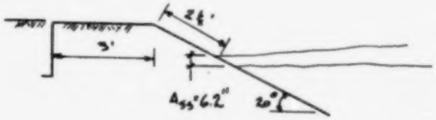
(2) OBTAIN LOAD-ELONGATION DATA



ϵ_{YIELD} = 11%

ϵ_{ULT} = 46%

(3) ESTIMATE MAX. STRAIN IN LCR DUE TO SETTLEMENT, ϵ_{MAX}



$L = 3 + 2\frac{1}{2} = 5\frac{1}{2}$ FT = 66"

$\Delta L = \Delta_{ss} / \sin\beta = 6.2" / \sin 20° = \underline{18.1 \text{ INCH}}$

$\epsilon_{MAX} = \frac{18.1}{66"} = 27.4\%$

(4) CALCULATE DESIGN RATIO

$DR_{YIELD} = \frac{11}{27.4} = 0.40$ NG

$DR_{ULT} = \frac{46}{27.4} = 1.67$ OK

Example No. 3.9

Cell Component: LEACHATE COLLECTION/REMOVAL SYSTEM

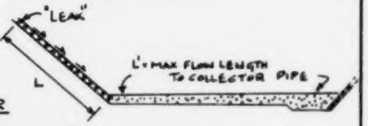
Consideration: TRANSMISSIVITY - RESPONSE TIME: CALCULATE THE MINIMUM TIME REQUIRED FOR LEACHATE ENTERING LCR TO BE DETECTED AT THE SUMP.

Required Material Properties	Range	Test	Standard
LCR DRAINAGE MEDIA - SIDEWALL			
• TRANSMISSIVITY, θ	$> 3\times10^{-5}$ m²/sec*	TRANSMISSIVITY	ASTM D4617
• POROSITY, n	.3 - .8	NONE	
LCR DRAINAGE MEDIA - BOTTOM SAND HYDRAULIC CONDUCTIVITY, K_{SAND}	$> 10^{-2}$ cm/sec	PERMEABILITY	ASTM D2434

*Draft MTG Minimum

Analysis Procedure:

ASSUMING SATURATED LCR



(1) CALC. 'TRUE' FLOW VELOCITY IN SYNTHETIC LCR

t = THICKNESS OF LCR UNLOADED (CONSERVATIVE)

$q = KiA$ (DARCY'S EQUATION)

V_s = APPARENT VELOCITY = $q/A = Ki$

$= [\theta/t]/i$ $\quad i = \Delta h/L$ = SLOPE OF SIDEWALL

V_t = TRUE VELOCITY = V_s/n

n = POROSITY, MEASURE OR CALCULATE

(2) CALC. 'TRUE' FLOW VELOCITY IN SAND LAYER

$[V_s]_{SAND}$ = APPARENT VELOCITY = $K i_{SAND}$

$[V_t]_{SAND}$ = TRUE VELOCITY = $[V_s]_{SAND}/n_{SAND}$

$n_{SAND} = 1 - \frac{\gamma_d}{G_s \gamma_w}$ $\quad \gamma_d$ = DRY UNIT WEIGHT OF SAND, γ_w = UNIT WEIGHT, WATER

G_s = SPECIFIC GRAVITY OF SAND

(3) CALCULATE TRAVEL TIME, T

$time = (t)_{SIDEWALL} + (t)_{SAND}$

$$T = \frac{L}{V_t} + \frac{L'}{[V_t]_{SAND}}$$

Design Ratio:

NOT APPLICABLE

References:

Example:

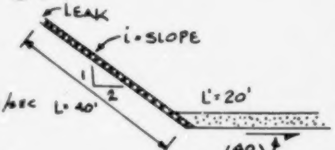
GIVEN:

SYNTHETIC SIDEWALL LCR

- TRANSMISSIVITY, $\theta = 1\times10^{-5}$ m²/sec @ $i = 0.5$
- THICKNESS = 2 cm
- POROSITY = 0.5

SAND BOTTOM LCR

- HYDRAULIC CONDUCTIVITY, $K = 1\times10^{-2}$ cm/sec
- DRY UNIT WEIGHT = 110 PCF
- SPECIFIC GRAVITY, $G_s = 2.65$
- $L' = 20$ FT.



$$i = \frac{\left(\frac{40}{\sqrt{5}}\right)}{20} = .89$$

(1) CALCULATE 'TRUE' FLOW VELOCITY IN SYNTHETIC LCR

$$V_s = [1\times10^{-5}\ \text{m}^2/\text{sec} / 2\text{cm}] / \left(\tfrac{1}{\sqrt{5}}\right)$$

$= .001$ M/SEC

$V_t = .001/.5 = .002$ M/SEC = $\underline{\underline{0.0073}}$ FT/SEC

(2) CALCULATE 'TRUE' FLOW VELOCITY IN SAND LAYER

$[V_s]_{SAND} = 1\times10^{-2} * .89 = .0089$ cm/sec

$n = 1 - \frac{110}{2.65\times62.4} = 0.33$

$[V_t]_{SAND} = .0089/.33 = .027$ cm/sec = $\underline{\underline{.88\times10^{-4}\ \text{FT/SEC}}}$

(3) CALCULATE TRAVEL TIME, T

$$T = \frac{40}{.0073} + \frac{20}{.88\times10^{-4}}$$

$= 5479_{sec} + 22580$ sec $=$ 7.8 HOURS

$=$ $\underline{\underline{0.3}}$ DAYS

Example No. 3.10

Cell Component: LEACHATE COLLECTION / REMOVAL SYSTEMS

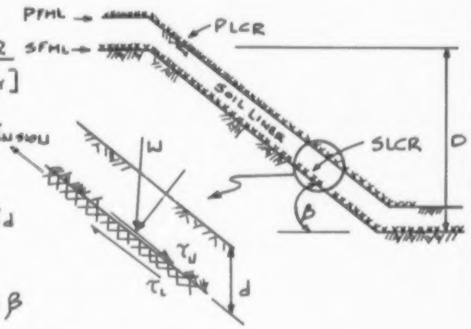
Consideration: STRENGTH - COMPOSITE PRIMARY LINER; VERIFY THAT SLCR CAN SUPPORT WEIGHT OF COMPOSITE PRIMARY LINER SYSTEM PRIOR TO PLACEMENT OF WASTE.

Required Material Properties		Range	Test	Standard
FRICTION ANGLE	SLCR-TO-SFML, δ_L SLCR TO-SOIL, δ_U SFML-TO-SOIL, δ_{UU}	10° TO 30° 20° TO 45°	DIRECT SHEAR	ASTM (TENTATIVE)
TENSILE STRENGTH OF LCR			WIDE WIDTH	ASTM D4595

Draft MTG Minimum

Analysis Procedure:

(1) EVALUATE TENSION IN SLCR
[INFINITE SLOPE ANALOGY]



TENSION = $\tau_U - \tau_L$

WHERE

$\tau_U = W\cos\beta \tan\delta_U$

W = WEIGHT SOIL LINER, γd

* $\tau_L = W\cos\beta \tan\delta_L$

TENSION = $[\tau_U - \tau_L] \times D/\sin\beta$

(2) OBTAIN LABORATORY TENSILE STRENGTH, SLCR

SEE EXAMPLE 3.7 → T_{MAX}

(3) CALCULATE DESIGN RATIO

$$DR = \frac{T_{MAX}}{TENSION}$$

* τ_L IS LIMITED BY ABILITY OF SFML TO TRANSFER SHEAR TO UNDERLYING SOIL. THEREFORE VERIFY THAT $\delta_{UU} > \delta_L$. IF NOT, SUBSTITUTE δ_{UU} IN THE EQUATION FOR τ_L

Design Ratio:

2.0-5.0 MINIMUM DEPENDING ON ANTICIPATED CONSTRUCTION LOADING

References:

Example:

GIVEN:

- SLOPE ANGLE, $\beta = 20°$
- SOIL LINER UNIT WT., $\gamma = 130$ PCF
- SOIL LINER THICKNESS, $d = 42$ INCHES
- FRICTION ANGLES: SLCR-TO-SFML, $\delta_L = 13°$
  - SLCR-TO-SOIL, $\delta_U = 28°$
  - SFML-TO-SOIL, $\delta_{UU} = 16°$
- CELL DEPTH, $D = 60$ FT

(1) EVALUATE TENSION IN SLCR

$W = d\gamma = \frac{42}{12} \times 130 = 455$ PSF

$\tau_U = W\cos\beta \tan\delta_U = 455 \times \cos 20° \times \tan 28°$
$= \underline{227}$ PSF

$\tau_L = W\cos\beta \tan\delta_L = 455 \times \cos 20° \times \tan 13°$
$= \underline{98.7}$ PSF

TENSION $= [\tau_U - \tau_L] \times D/\sin\beta = [128] * 60/\sin 20° = \underline{\underline{22000 \text{ lb/ft}}}$

(2) OBTAIN LABORATORY TENSILE STRENGTH, SLCR

SEE EXAMPLE 3.7
$T_{MAX} = 4950$ lb/ft

(3) CALCULATE DESIGN RATIO

$$DR = \frac{T_{MAX}}{TENSION} = \frac{4950}{22000} = 0.22 \quad \underline{N.G.}$$

NOTE: EXTREME LOADING CONDITION FOR THIS CASE WILL TYPICALLY OCCUR DURING CONSTRUCTION. THE SOIL LINER MAY BE CONSTRUCTED OVERSIZED AND THEN TRIMMED. ADDITIONALLY, THE WEIGHT AND DYNAMIC LOADS FROM FIELD EQUIPMENT MAY ADD TO THE DRIVING FORCE

Example No. 3.11

Cell Component: Flexible Membrane Liner

Consideration: Psuedo Permeability via WVT; calculate the Psuedo-Permeability of a membrane using Water Vapor Transmissial Test data.

Required Material Properties	Range	Test	Standard
Water Vapor Transmission, WVT	10 - 0.1 gm/m²-day	WVT	ASTM E96

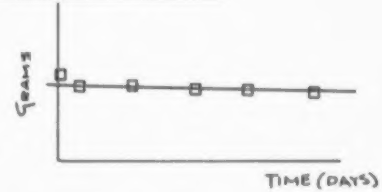
Draft MTG Minimum

Analysis Procedure:

(1) Calculate WVT from Expermental Data

$$WVT = \frac{g \times 24}{t \times a}$$

g = weight change, grams
t = elapsed time, hours
a = area of specimen, m²



(2) Calculate Permeance from WVT

$$\text{Permeance} = \frac{WVT}{\Delta P} = \frac{WVT}{S(R_1 - R_2)}$$

S = saturation vapor pressure @ test temp
R_1 = relative humidity within cup
R_2 = relative humidity outside cup

(3) Calculate Psuedo-Permeability from Permeance

Permeability, K_{Psuedo} = Permeance x membrane thickness

Design Ratio:

Not Applicable

References:

Koerner and Lord (1984)

Example:

Given:

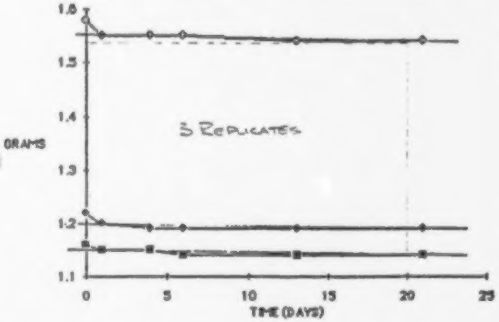
- 60 mil HDPE membrane
- Sample area = 0.003 m²
- Temperature = 105°F → Saturation Pressure, S = 57 mm Hg.
- Humidity difference, $R_1 - R_2 = 60\%$

(1) Calculate WVT from Experimental Data

g = 0.01 grams
t = 20 day × 24
a = 0.003 m²

$$WVT = \frac{0.01 \times 24}{20 \times 24 \times 0.003}$$

= 0.167 g/m²-day



(2) Calculate Permeance from WVT

$$\text{Permeance} = \frac{0.167}{57 \times 0.60} = 0.0048 \text{ metric perm}$$

note

(3) Calc Psuedo-Permeability from Permeance

Psuedo-Permeability $K_{\text{Psuedo}} = 0.0048 \times 60 = 0.29$ metric perm-mils

[1 metric perm-mil = 2.167×10^{-12} cm/sec]

$$\therefore K_{\text{Psuedo}} = 0.62 \times 10^{13} \text{ cm/sec}$$

Example No. 3.12

Cell Component: FLEXIBLE MEMBRANE LINER

Consideration: DEMINIMIS PERMEABILITY, CALCULATE THE FACTOR-OF-SAFETY BASED ON ACTUAL LEAKANCE VERSUS DE MINIMIS LEVEL (1 GALLON/ACRE/DAY)*

Required Material Properties	Range	Test	Standard
VAPOR TRANSMISSION OF FML Draft MTG Minimum		PERMEANCE	ASTM E96

Analysis Procedure:

(1) CALCULATE PERMEABILITY OF FML FROM PERMEANCE

K = PSUEDO PERMEABILITY = PERMEANCE × t

t = FML THICKNESS

(2) CALCULATE VAPOR DIFFUSION THROUGH FML

$q_{FML} = K_{PSUEDO}\, i A T$

i - HEAD $\quad \frac{\Delta H}{t}$ $\qquad \Delta H = 1$ FT. STATUTORY MAX.

A - AREA

(3) CALCULATE DESIGN RATIO

$DR = \frac{q_{STAT}}{q_{FML}}$ $\qquad q_{STAT} = 1$ GAL/ACRE/DAY

Design Ratio:

$DR_{MIN} = 2.0$

References:

KOERNER AND LORD (1984)

Example:

GIVEN:

- 80 MIL HDPE
- PERMEANCE = 0.0048 METRIC PERM (SEE EXAMPLE 3.12)

(1) CALCULATE PSUEDO PERMEABILITY OF FML

$K_{PSUEDO} = 0.0048 \times 80 = 0.384$ METRIC PERM-MIL

OR $\quad K_{PSUEDO} = 832 \times 10^{-13}$ CM/SEC $= \underline{\underline{3.27 \times 10^{-13}}}$ INCH/SEC

(2) CALCULATE FLOW THROUGH FML

$q_{FML} = 3.27 \times 10^{-13} \times \frac{12"}{.06"} \times 1$ IN²

$= 6.55 \times 10^{-11}$ IN³/IN²/SEC

[1 GALLON/ACRE/DAY = 4.26×10^{10} IN³/IN²/SEC]

$\therefore \quad q_{FML} = \frac{6.55 \times 10^{-11}}{4.26 \times 10^{-14}} = \underline{\underline{0.153}}$ GAL/ACRE/DAY

(3) CALCULATE DESIGN RATIO

$DR = \frac{1.0}{0.153} = \underline{\underline{6.5}}$ $\qquad$ OK!!

Example No. 3.13

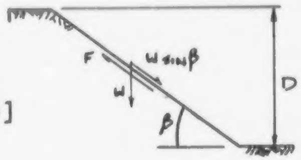
Cell Component: FLEXIBLE MEMBRANE LINER

Consideration: TENSILE STRESS - LINER WEIGHT; EVALUATE ABILITY OF FML TO SUPPORT ITS OWN WEIGHT ON THE SIDE SLOPES.

Required Material Properties	Range	Test	Standard
FML SPECIFIC GRAVITY, G	0.92 to 1.4		
FRICTION ANGLE • FML-TO-LCR, S_L	10° to 45°	DIRECT SHEAR	PROPOSED ASTM
FML THICKNESS, t	30 TO 180 MIL		
FML YIELD STRESS, σ_Y Draft MIG Minimum	1000 TO 5000 (PSI)	TENSILE	ASTM D638

Analysis Procedure:

(1) CALCULATE FML TENSILE FORCE, T



$T = W \sin\beta - F$

WHERE

W = LINER WEIGHT

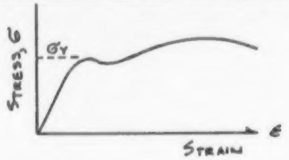
$= [G\gamma_w t][1 \times D/\sin\beta]$

$F = W \cos\beta \tan S_L$

(2) CALCULATE FML TENSILE STRESS, σ

$\sigma = T/A$ WHERE A = AREA = 1' × t

(3) OBTAIN LABORATORY FML YIELD STRESS, σ_Y



(4) CALCULATE DESIGN RATIO

$DR = \sigma_Y / \sigma$

Design Ratio:

$DR_{MIN} = 10$ ON YIELD

References:

Example:

GIVEN:

- 60 MIL HDPE
- FML SPECIFIC GRAVITY, G = 0.941
- FRICTION ANGLE
  FML-TO-LCR, $S_L = 20°$
- D = 120 FT
- β = 30°

(1) CALCULATE FML TENSILE FORCE, T

$W = [0.941 \times 62.4 \times \frac{.060}{12}] = [1 \times 120/\sin 30°]$

$= 70.5$ lb/FT

$F = 70.5 \cos 30° \tan 20°$

$= 22.2$ lb/FT

$T = 70.5 \sin 30° - 22.2$

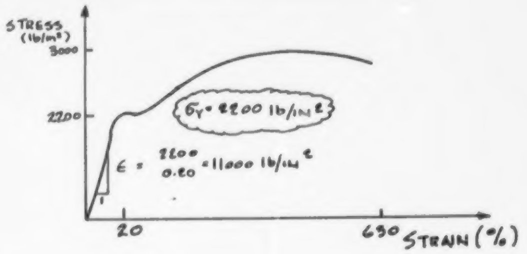
$= \underline{\underline{13.0 \text{ lb/FT}}}$

(2) CALCULATE FML TENSILE STRESS, σ

$\sigma = 13.0/(1 \times \frac{.060}{12}) = 2600$ lb/FT²

$= \underline{\underline{18.0}}$ lb/IN²

(3) OBTAIN LABORATORY FML YIELD STRESS



(4) CALCULATE DESIGN RATIO

$DR = 2200/18 = \underline{\underline{122}}$ OK

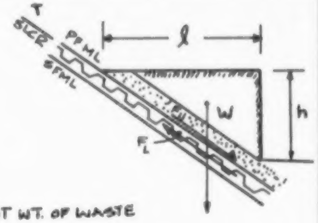
Example No. 3.14

Cell Component: FLEXIBLE MEMBRANE LINER

Consideration: TENSILE STRESS - DOWN DRAG AT FILLING; CALCULATE FML STRESS GENERATED DURING CONSTRUCTION OF INTERIOR CELL ADJACENT TO SIDE WALLS OF FACILITY

Required Material Properties	Range	Test	Standard
FRICTION ANGLES			
• PLCR-TO-PFML, δ_U	10°-30°	DIRECT-SHEAR	ASTM (TENTATIVE)
• PFML-TO-SLCR, δ_L	10°-30°		
TENSILE STRENGTH OF FML Draft MTG Minimum			

Analysis Procedure:



(1) CALCULATE DOWN-DRAG FORCE ON FML, T

$$T = F_U - F_L$$

WHERE $F_U = W\cos\beta \tan\delta_U$

$F_L = W\cos\beta \tan\delta_L$ **

$W = \frac{1}{2}(h\ell)\gamma$ γ = UNIT WT. OF WASTE

(2) CALCULATE FML TENSILE STRESS, σ

$$\sigma = T/t$$ t = THICKNESS OF FML

(3) OBTAIN LABORATORY FML YIELD STRESS, σ_Y

SEE EXAMPLE 3.14

(4) CALCULATE DESIGN RATIO

$$DR = \sigma_Y / \sigma$$

Design Ratio:

DR_{MIN} = 5.0 ON YIELD

References:

Example:

GIVEN:

- CELL THICKNESS, h = 5'
- UNIT WT. WASTE, γ = 80PCF
- SLOPE ANGLE, β = 30°
- FRICTION ANGLES
  - PLCR-TO-PFML, δ_U = 19°
  - PFML-TO-SLCR, δ_L = 12°
- 60 MIL HDPE

(1) CALCULATE DOWN-DRAG FORCE ON FML, T

$$W = \frac{1}{2}(h\ell)\gamma = \frac{1}{2}(5\times(5/\tan 30^\circ))80 = 1732 \text{ lb/FT}$$

$$F_U = 1732 \times \cos 30^\circ \times \tan 19^\circ = 516 \text{ lb/FT}$$

$$F_L = 1732 \times \cos 30^\circ \times \tan 12^\circ = 319 \text{ lb/FT}$$

$$T = 516 - 319 = \underline{197} \text{ lb/FT}$$

(2) CALCULATE FML TENSILE STRESS σ

$$\sigma = 197/\left(\frac{.060}{12}\right) = 39400 \text{ lb/FT}^2 = 274 \text{ lb/IN}^2$$

(3) OBTAIN LABORATORY FML YIELD STRESS, σ_Y

SEE EXAMPLE 3.14 → σ_Y = 2200 lb/IN^2

(4) CALCULATE DESIGN RATIO

$$DR = 2200/274 = \underline{8.0}$$ OK

Example No. 3.15

Cell Component: FLEXIBLE MEMBRANE LINER

Consideration: LOCALIZED SUBSIDENCE : EVALUATE STRAINS INDUCED IN FML BY LOCALIZED SUBSIDENCE.

Required Material Properties	Range	Test	Standard
· TENSILE STRENGTH OF FML		WIDE-WIDTH	ASTM-D
· THICKNESS OF FML			ASTM
· SOIL-FML FRICTION ANGLE Draft MTG Minimum		DIRECT SHEAR	ASTM (TENTATIVE)

Analysis Procedure:

(1) ESTIMATE SUBSIDENCE GEOMETRY

- WIDTH OF SUBSIDENCE, L ≈ WIDTH OF UNDERLYING EXCAVATION + 45° EXTENSION THROUGH SUPPORT LAYER
- DEPTH OF SUBSIDENCE, S (MINIMUM) ≈ 20% DEPTH OF EXCAVATION

(2) OBTAIN UNIFORM STRAIN FROM FIGURE 3.4

- SETTLEMENT RATIO = $\frac{\text{DEPTH}}{\text{WIDTH}} = \frac{S}{L}$

  → ε

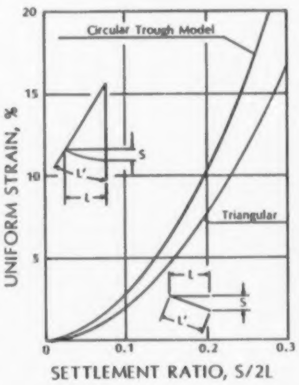
(3) CALCULATE ADDITIONAL DEFORMABLE LENGTH

$$X = \frac{f_y d}{2 A f_t}$$

f_y = ULTIMATE STRESS FOR FML
d = THICKNESS OF FML
A = NORMAL STRESS
f_t = FRICTION COEFFICIENT

(4) REVISE STRAIN

$$\varepsilon' = [\varepsilon \, L] / [L + 2x/2]$$



Design Ratio:

NOT APPLICABLE

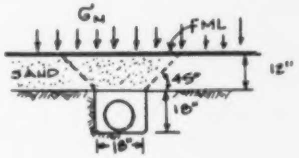
References:

KNIPSCHIELD (1985)

Example:

GIVEN:

- 60 MIL HDPE
- TENSILE STRENGTH = 1500 psi
- SOIL-FML FRICTION = 18°
- σ_N = 6 KSF



(1) ESTIMATE SUBSIDENCE GEOMETRY

- WIDTH = 18" + 2×12" = 42"
- DEPTH = .2 × 18" = 3.6"

} SETTLEMENT RATIO = 0.086

(2) OBTAIN UNIFORM STRAIN, FIG. 3.4

SETTLEMENT RATIO = 0.086 → ε = 2.0%

(3) CALCULATE ADDITIONAL DEFORMABLE LENGTH

$$X = \frac{1500 \times .060}{2 \times \left[\frac{6 \times 1000}{144}\right] \times .325}$$

$= 3.3$ INCH

$\tan^{-1} 18° = .325$

(4) REVISE STRAIN

$$\varepsilon' = \frac{.02 \times 42"}{42" + 3.3} = .0185 = \underline{\underline{1.85\%}} \text{ STRAIN}$$

STRAIN AT YIELD = 20% $\geq$ ∴ OK

(ε_{ULT} = +600%)

Example No. 3.16

Cell Component: FLEXIBLE MEMBRANE LINING

Consideration: FML ANCHORAGE - CALCULATE ANCHOR CAPACITY FOR FML PLACED IN VARIOUS ANCHORAGE CONFIGURATIONS.

Required Material Properties	Range	Test	Standard
• SOIL/FML FRICTION ANGLE	12-20°	DIRECT SHEAR	ASTM PROPOSED
• SOIL FRICTION ANGLE	25-38°	TRIAXIAL	ASTM PROPOSED

Draft MTG Minimum

Analysis Procedure:

(1) DEFINE ANCHOR VARIABLES

- GEOMETRY
  - SLOPE ANGLE β
  - EMBEDMENT LENGTH, L
  - SOIL COVER, d_{cs}
  - ANCHOR BURIAL, d_{AT}
- MATERIAL
  - SOIL FRICTION ANGLE, ϕ
  - SOIL/FML FRICTION ANGLE, δ
  - SOIL UNIT WEIGHT, γ_{cs}

(2) SOLVE FOR ANCHOR CAPACITY

HORIZONTAL ANCHOR

$$T = \frac{qL\tan\delta}{(DR)\cos\beta - \sin\beta\tan\delta}$$

"V" ANCHOR

$$T = \frac{\tan\delta\left[q\left(L - L_V + \frac{L_V}{\cos i}\right) + \frac{d_V L_V \gamma_{cs}}{2\cos i}\right]}{(DR)\cos\beta - \sin\beta\tan\delta}$$

CONCRETE ANCHOR

$$T = \frac{qL\tan\delta + (K_P\, K_A)[.5\gamma_{cs}d_{AT}^2 + qd_{AT}]}{(DR)\cos\beta - \sin\beta\tan\delta}$$

ANCHOR TRENCH

$$T = \frac{qL\tan\delta + (K' + K_A)\tan\delta[.5\gamma_{cs}d_{AT}^2 + qd_{AT}]}{(DR)\cos\beta - \sin\beta\tan\delta}$$

$K' = K_P$ OR K_o

REF FIGURES 3.9 & 3.10

Design Ratio:

NOT APPLICABLE

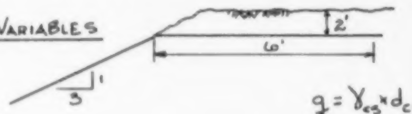
References:

Example:

GIVEN: GEOMETRY
- $\beta = 18.4°$ (3:1 SLOPE)
- L = 6 FT
- $d_{cs} = 2'\text{-}0$
- DR = 1.5 MINIMUM

SOIL
- $\phi = 35°$
- $\delta = 13°$
- $\gamma_{cs} = 120$ PCF

(1) DEFINE VARIABLES



$q = \gamma_{cs} \times d_{cs} = 120 \times 2 = 240$ PSF

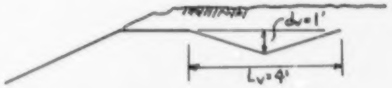
(2) SOLVE FOR ANCHOR CAPACITIES

• HORIZONTAL (AS SHOWN)

$$T = \frac{240 \times 6 \times \tan 13°}{1.5\cos 18.4° - \sin 18.4° \tan 13°} = \underline{\underline{248 \text{ lb/ft}}}$$

• "V" TRENCH

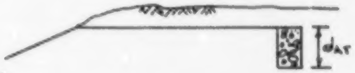
$\left.\begin{array}{l} -\ L_V = 4' \\ -\ d_V = 1' \end{array}\right\} i = 26.5°$



$$T = \frac{\tan 13°\left[240\left(6.4 + \frac{4}{\cos 26.5°}\right) - \frac{1 \times 4 \times 120}{2\cos 26.5°}\right]}{1.339} = \underline{\underline{313}} \text{ lb/ft}$$

• CONCRETE ANCHOR

- $d_{AT} = 2'\text{-}0''$
- $\phi = 35° \Rightarrow K_A = .27$ $K_P = 3.7$



$$T = \frac{240 \times 6 \times \tan 13° + (3.7 - .27)[0.5 \times 120 \times 2^2 + 240 \times 2]}{1.339} = \underline{\underline{1990 \text{ lb/ft}}}$$

• ANCHOR TRENCH

- $d_{AT} = 2'\text{-}0''$
- $\phi = 35° \Rightarrow K_o = .426$

$$[T]_{KP} = \frac{240 \times 6 \times \tan 13° + (3.7 + .27)\tan 13°[.5 \times 120 \times 2^2 + 240 \times 2]}{1.339} = \underline{\underline{493 \text{ lb/ft}}}$$

$$[T]_{K_o} = \frac{240 \times 6 \times \tan 13° + (.426 + .27)\tan 13°[.5 \times 120 \times 2^2 + 240 \times 2]}{1.339} = 334 \text{ lb/ft}$$

Example No. 3.17

Cell Component: FLEXIBLE MEMBRANE LINING

Consideration: STABILITY OF SOIL COVER - VERIFY THAT SOIL COVER WILL NOT SLIDE ON FML. ALSO VERIFY ANCHOR CAPACITY AND STRESS IN FML.

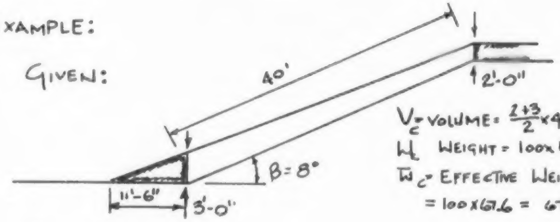
Required Material Properties	Range	Test	Standard
SOIL COVER - FML FRICTION, δ_u	10-20°	DIRECT SHEAR	PROPOSED ASTM
FML-LCR FRICTION, δ_L	8-15°	DIRECT SHEAR	
YIELD STRESS OF FML Draft MTG Minimum	1000-2200 Psi	TESION	ASTM D638

Analysis Procedure:

REFERENCE FIG 3.16

EXAMPLE:

GIVEN:



V_c = VOLUME = $\frac{2+3}{2} \times 40 = 100\ FT^2$

W_c WEIGHT = 100 × 130 = 13000 lb.

$\overline{W}_c$ = EFFECTIVE WEIGHT = 100 × 67.6 = 6760 lb.

COVER SOIL

$\gamma_{SAT} = 130\ PCF \rightarrow \gamma_b = 67.6\ PCF$

SOIL/FML BOND

$\delta = 18°$ $c = 0$

FML/LCR BOND

$\delta = 12°$ $c = 0$

FML

THICKNESS = 45 MIL, YIELD STRESS = 1800 psi

Design Ratio:

$DR_{MIN} = 1.2$ SLIDING

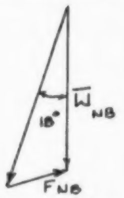
References:

GIROUD AND AH-LINE, 1984

Example:

(CONT)

- SOLVE NEUTRAL BLOCK FORCE POLYGON



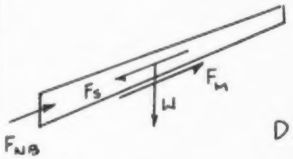
$\overline{W}_{NB} = V_{NB} \gamma_b$

$V_{NB} = \frac{1}{2}\ 3 \times 11.5 = 17.25\ FT^2$

$\overline{W}_{NB} = 1166\ lbs$

$F_{NB} = \underline{420\ lbs}$

- SOLVE FOR SLIDING STABILITY

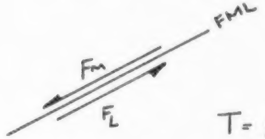


$F_M = 6760 \times \cos 8° \times \tan 18°\ 2175\ lb$

$F_S - 100 \times 62.4 \times \sin 8° = 868\ lb$

$$DR = \frac{420 + 2175}{868 + 13000 \sin 8°} = \underline{\underline{1.01}}\ \text{NG}$$

- SOLVE FOR MEMBRANE TENSION



$F_L = 13000 \times \cos 8° \times \tan 12° - 2736$

$T = 2175 - 2736 \approx -561$

BUT T CANNOT BE COMPRESSIVE $\therefore$ T = 0

AND $\sigma_{FML} = 0$

- VERIFY ANCHOR CAPACITY

SINCE T = 0, ANCHOR IS NOT STRESSED

Example No. 3.18

SECTION IV

DESIGN OF COMPONENTS WITHIN CELL

Components placed within the cell and on the primary FML include those required to meet minimum guidance criteria for the land disposal cell and additional components required for operation of the facility. Statutory related components within the cell include the standpipe system required to both monitor and remove leachate from the primary LCR systems and a witness system for monitoring the secondary LCR system. Operations-related components within the cell include the ramp structure required for truck access to below grade cells and interior berm walls used to segregate wastes or operational functions. These operations components must be designed to both perform under transient services loads and not fail the statutory cell components during either the operation or post-closure monitoring periods.

RAMP AND TRAFFIC CONSIDERATIONS

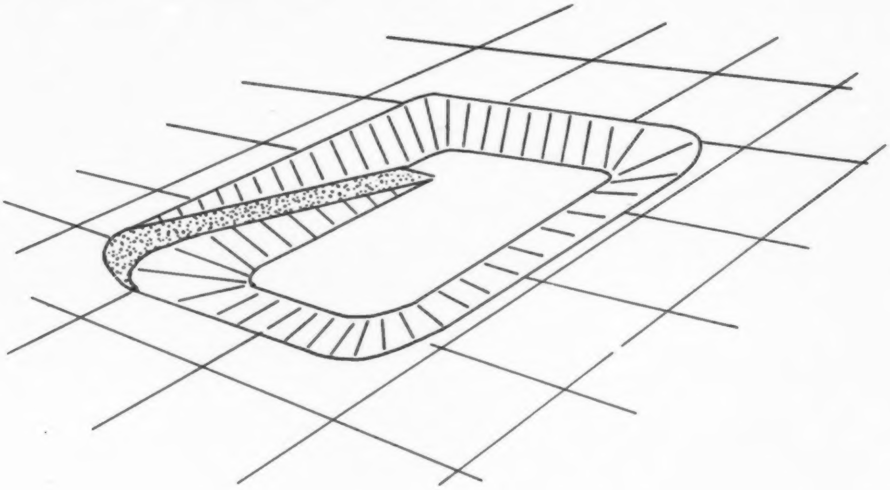


Figure 4.1 Geometry of Typical Ramp

Heavily loaded vehicles must enter the cell during both the placement of waste within the facility and during construction of cells. These vehicles require a roadway that is wide enough for typical highway transport vehicles or construction equipment and with a low enough grade that these vehicles can routinely climb out of the cell. Typically this will require a roadway 15 to 18 feet in width having a grade of no more than 10-12%. This roadway profile will generally be constructed during the initial excavation of the below grade cell and will define the profile of the cell through placement of the primary LCR system. The geometry of a typical ramp is shown on Figure 4.1. Above grade cells will not require internal ramp structures, and cells only partially below grade will have a greatly reduced ramp structure. The geometry of ramps is therefore very site specific with no 'standard' ramp detail applicable to all sites.

Design of this structure is complicated by the low friction angle that exists between typical FML materials and soil, the need to use the ramp during the construction process, and the statutory requirement that the double FML and LCR systems be continuous within the cell. The ramp is normally used during construction of the cell and must support traffic that includes off-road haulers, e.g. pans, that may produce significantly higher loads than the eventual operational loadings. During this time, the ramp will be exposed to seasonal effects that include freeze-thaw and precipitation. A cross section of a typical ramp in a double FML cell is shown on Figure 4.2 and raises significant design and construction questions.

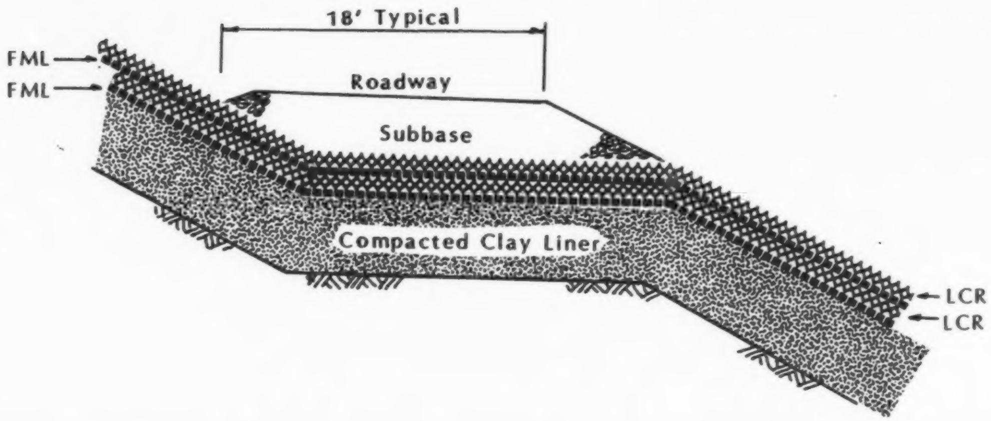


Figure 4.2 Cross-Section of Typical Access Ramp

The design of the ramp must address the following loadings and potential failure mechanisms:

1) Shear failure along the axis of the roadway caused by the impact of breaking traffic and the weight of the roadway.
2) Shear failure along the axis of the roadway caused by hydrostatic pressures from surface water draining through the roadway.
3) Puncture of the primary FML caused by impacting wheel loads forcing the subbase stone into the membrane.
4) Ravelling of the roadway shoulder due to lack of confinement.
5) Breakup of the roadway caused by freeze-thaw conditions.

Geosynthetic considerations are included in the first four mechanisms while the freeze-thaw mechanism is typically eliminated by the use of granular soils in the roadway base and subbase.

Shear failure of the roadway caused by the impact of breaking traffic and the weight of the roadway is the classical sliding brick on an incline problem. The static forces from the weight of the roadway combine with the dynamic forces generated by the breaking of traffic on the roadway act to move the roadway down the incline. The level of breaking force depends on both the size and speed of vehicles and the number that are allowed on the ramp at a given time. Many facilities have limits on vehicle traffic allowed on the ramp at a given time. However, a conservative design is ensured only by designing for a fully occupied ramp. Example 4.1 presents the analysis used to verify the sliding stability of the roadway. The low factor-of-safety allowed in this mode under full service load is a reflection of the limited life of the ramp. As waste is added to the cell, the ramp decreases in length and accumulated slippage is buried. The limiting frictional bond is typically between an FML and a synthetic LCR. This bond can be significantly improved if a thin (3 inch) layer of sand is placed between the LCR and the FML. This technique does not work with geonets.

The ramp forms a catch basin that must be designed to handle the surface water runoff coming from the cell sidewalls. The particulars of this design will obviously be influenced by the anticipated peak rate of rainfall. The roadway must incorporate a granular subbase or a drainage system capable of handling this volume of runoff without allowing the build up of pore water pressure beneath the roadway. A drainage system embedded within the roadway will present operational difficulties since the outlet of the drainage system will either be quickly buried in waste or will require frequent excavation to maintain drainage. Example 4.2 shows the general method used to calculate the total runoff and to verify the flow capacity of the gravel within the roadway profile. Typically the roadway section will not be able to handle the full surface water flow and a ditch is required on the inside of the roadway.

The same gravel required to allow drainage of surface water runoff will present a significant threat of puncture to the underlying FML. The roadway profile must be designed to both support the vehicle wheel loads with a minimum amount of rutting and to minimize the puncture or tearing forces applied to the FML. Both design functions are good applications for geosynthetics. A roadway surface can be reinforced through the addition of a single layer of geotextile or geogrid. The load carrying capacity of such a system can be estimated using a simple limit equilibrium technique first developed by Barenburg(1975), and later modified by Giroud (1981). These design procedures were developed for soils having a CBR (California Bearing Ratio) less than 4. The heavily compacted clays forming half of the lower liner will have CBR values considerably in excess of 4. The use of a reinforced roadway will therefore produce little or no benefit.

Puncture resistance of the FML beneath the roadway can be improved by using a thicker roadway section to reduce the stress level acting at the elevation of the FML, or by providing a cushion layer of sand or geosynthetic immediately above the FML. The use of an excessively thick roadway section is detrimental in that both expensive air space is wasted and because the weight of the driving force acting to slide the roadway down the ramp is increased. Therefore, the optimum design will use the minimum roadway thickness required to prevent puncture of the FML. The limiting contact pressure that the FML can tolerate is influenced by the cushion layer above and below it (see Figures 3.9-10, Koerner,1986). Assuming that a sand or geosynthetic cushion is used, the limiting contact stress can be evaluated in the laboratory as the normal pressure at which the cushion material begins to flow into the FML. Failure is typically assumed when the penetration exceeds 10% of the thickness of the FML. The minimum roadway thickness can then be evaluated using the procedure given in Example 4.3 using the most severe wheel loading. The use of a geotextile as the cushion layer for the FML is limited by the low coefficient of friction between the two materials. This can be improved if a thin layer of sand is placed between the geotextile and the FML.

INTERIOR BERMS

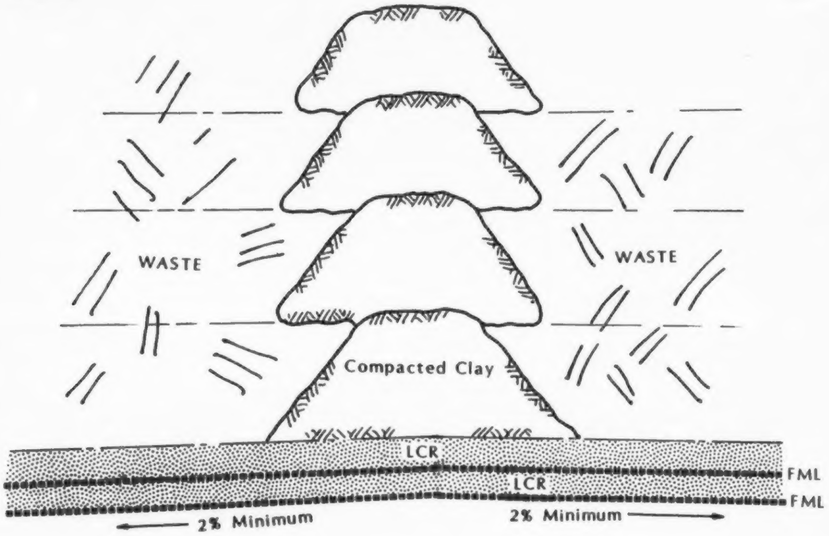


Figure 4.3 Interior Berm - Waste Separation

Berms are constructed within a waste disposal cell to segregate differing waste types or in some instances to provide a temporary boundary for an above ground facility to be built in phases. Such berms must provide an effective hydraulic barrier without requiring excessive air space or disrupting the continuity of the underlying LCR and FML systems. It is normal practice, however, to segregate the leachate that enters the primary LCR from each of the cells. This is accomplished to varying degrees by adjusting the contours of the LCR-FML system beneath the cells. The simplest interior berm involves placing the berm lift by lift during operation of the facility and minor contour changes to the LCR-FML systems. This system is shown on Figure 4.3. By constructing the berm in lifts as the waste is placed, its cross section is reduced to that required for hydraulic considerations and not for stability. Materials used for construction of the berm must have a permeability equivalent to that used in the liner or less than $1x10^{-7}$ cm/sec (EPA, 1985).

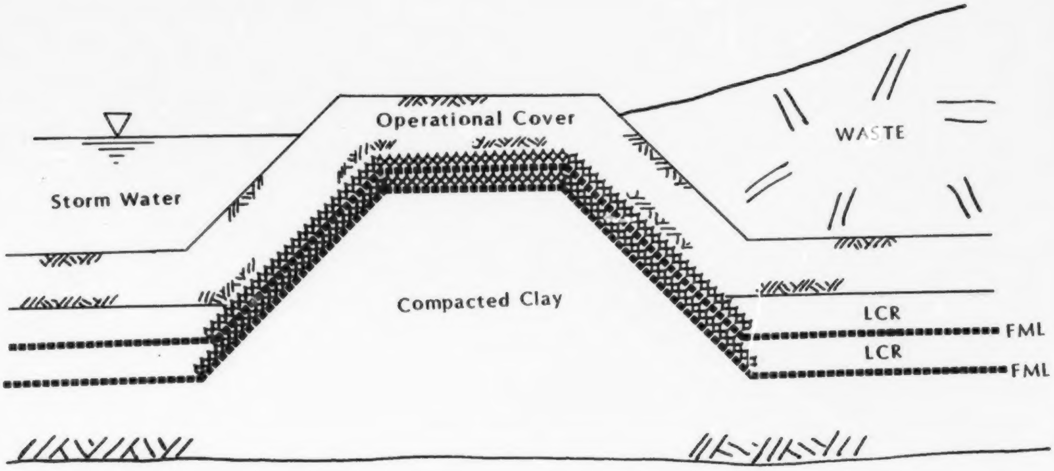


Figure 4.4 Interior Berm - Operations

More elaborate berms have been constructed when a greater degree of separation between the interior cells is desired or when operational needs dictate. Figure 4.4 shows an interior berm designed to separate the active landfill cell from a temporary storm water retention cell. To provide ample capacity for the storm water retention cell, the interior berm must be constructed to full section initially and not in lifts as the waste is placed. As such, the internal stability of these berms must be verified using conventional slope stability analyses. Complete segregation of the wastes within the LCR system can be obtained using an FML seal placed between the primary and secondary FMLs.

Large down-drag force can be generated on the berms as waste settles within the cells. These down-drag forces can increase the normal forces acting on synthetic systems underlying the berms and should be considered. Additionally, the berms are less compressible than the waste materials which may produce significant long term post-closure subsidence features. Methods for evaluating the magnitude of such differential settlements are reviewed by Murphy and Gilbert (1987). Such settlements are a major concern in the design of the cap system placed over the completed cell. These considerations are reviewed in Section V.

STANDPIPE for PRIMARY LCR

Single or multiple standpipes are usually provided as a means of monitoring and draining leachate that accumulates within the primary LCR system. Standpipes are therefore located at the low point of the collection system or subsystem and create a sump. Each standpipe houses and provides access to a pump used in removing the leachate that collects in the sump. During operation of the facility, the standpipe may also serve as a drain for surface runoff that occurs within the cell. The standpipe itself is typically made of concrete or HDPE pipe that is placed as the cell fills up with waste. A combined standpipe/drain detail is shown on Figure 4.5. This standpipe has an outer zone of gravel that is retained during operations by fencing.

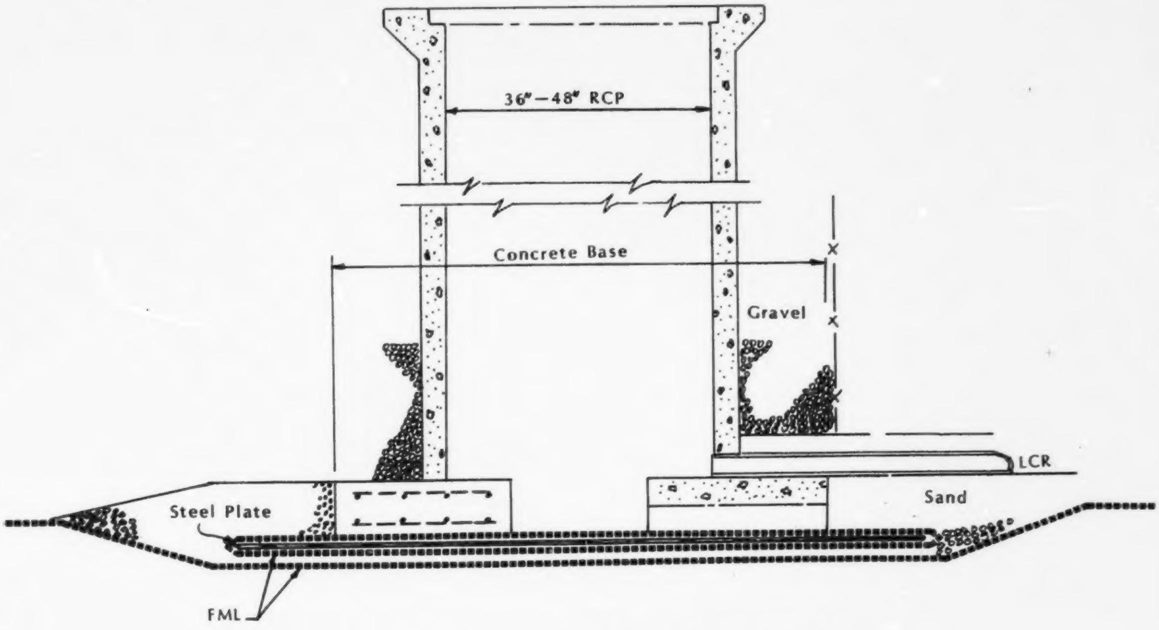


Figure 4.5 Standpipe/Drain - Details

Down-Drag Forces

Design considerations for standpipes reflect the potential for large down-drag forces in the standpipe due to settlement of the waste and for potential clogging of the standpipe by surface water runoff. Down-drag forces acting on the standpipe are caused by the differential settlement that occurs between the compressible waste fill and the rigid standpipe. The level of force is influenced by the amount of settlement but is limited by the bond between the soil and the standpipe. Due to uncertainties in estimating the amount of settlement the waste will experience, the limiting bond force is used for design.

The limiting bond force can be estimated based on the shear strength of the surrounding soil and the soil-standpipe friction angle. Note that the 'surrounding soil' may be stone or gravel, waste materials, or operational cover soil which has great variability. Procedures for estimating down-drag forces are commonly used in the design of deep foundations (e.g. piles) in underconsolidated soils. Knowing the friction or adhesion between the soil and the standpipe, the down-drag force can be calculated using the procedure demonstrated in Example 4.4. This procedure neglects the time-dependent increase in the down-drag force and only calculates the ultimate or limit down-drag force. Vesic (1977) indicates that down-drag forces can be fully developed with settlements as low as 0.6 inch.

Reductions in the magnitude of the down drag force require that the bond between the soil and the standpipe be reduced. This can be accomplished by using a 'lubricant' between the two materials or by isolating the standpipe from the waste as shown on Figure 4.6. Lubricants used to reduce down-drag forces may be actual grease, a bituminous coating, or a synthetic membrane. While the low coefficient of friction between soils and most membranes causes slope related stability problems, here this poor bond can be used advantageously. The influence of lubricants on down-drag forces calculated is shown in Example 4.4. This example assume that the use of a bituminous coating can lead to a six fold reduction in downdrag forces. Vesic(1977) reported reduction factors ranging from 6 to 15 based on measured field data in clays and silts.

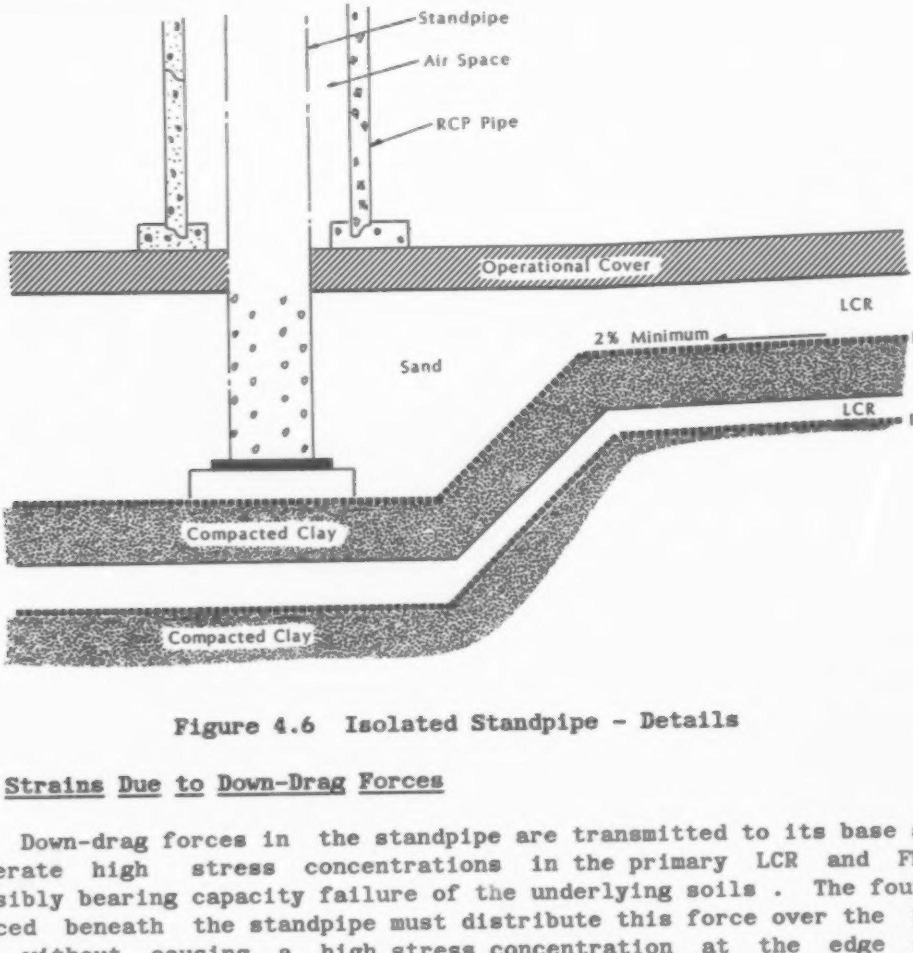


Figure 4.6 Isolated Standpipe - Details

FML Strains Due to Down-Drag Forces

Down-drag forces in the standpipe are transmitted to its base and can generate high stress concentrations in the primary LCR and FML and possibly bearing capacity failure of the underlying soils . The foundation placed beneath the standpipe must distribute this force over the primary LCR without causing a high stress concentration at the edge of the foundation pad that could cause a puncture-type failure of the membrane. The foundation system shown on Figure 4.5 incorporates a steel plate beneath the concrete pad to allow a transition and avoid such stress concentrations. Care must be taken to avoid making the plate overly rigid and the FML must be protected from its edges.

The FML beneath the standpipe will have to conform to the vertical displacements of the standpipe foundation. These displacements are influenced by the relative stiffness of the foundation to the stiffness of the underlying clay subgrade. Additionally, the displacements result from both elastic deformations and consolidation of the underlying clay. The amplitude of elastic displacements are given by

$$D_{elast} = \frac{Pa}{E} (1 - v^2) K \qquad \text{Eq(4.1)}$$

where P is the average contact pressure of the foundation, a is the foundation radius, E is the subgrade modulus, v is Poisson's ratio for the subgrade, and K is a variable that depends upon the stiffness of the foundation. Values of K for rigid and flexible foundations are shown on Figure 4.7a. The consolidation induced settlement of the foundation must be added to the above elastic value. It is influenced by the distribution of vertical contact stresses acting on the base of the foundation. This distribution is influenced by the stiffness of the foundation as shown on Figure 4.7b. For the flexible foundation, the consolidation settlements will be similiar in distribution to the elastic deformations of a flexible foundation but typically larger in magnitude. A rigid foundation will have consolidation settlements similiar to the elastic settlements but again typically larger.

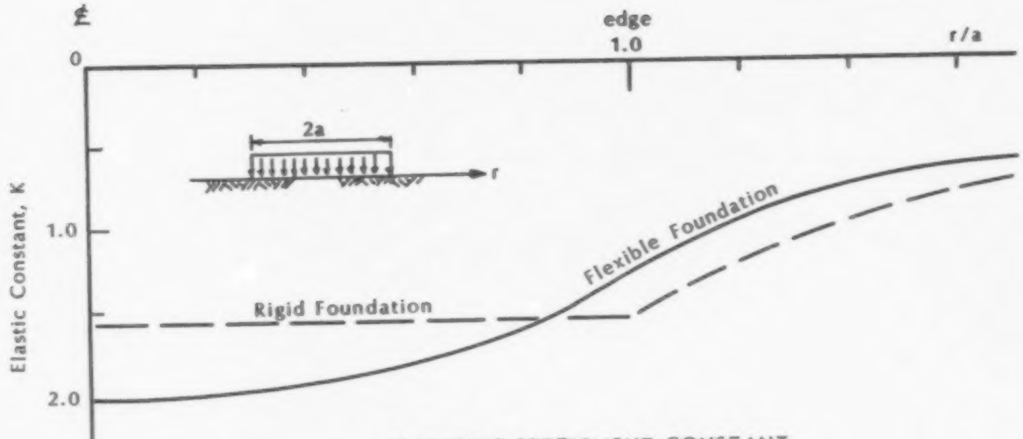
Two methods can be used for determining the maximum strain in the FML due to the standpipe induced vertical settlements. The first method makes the conservative assumption that no slippage occurs between the FML and the bottom of the foundation, such that the maximum strain in the FML will occur at the edge of the foundation. The strain in the FML is then calculated from the change in length of the interface surface. This is appropriate for flexible foundations. The second method assumes that the entire strain in the FML due to the vertical deflection of the foundation occurs at the edge of the plate. This assumption produces an apparent strain an order of magnitude larger than the first method and is appropriate only for rigid foundations. Both methods for estimating strain are shown on Figure 4.7c and are demonstrated in Example 4.5. Evaluating foundation stiffness is left to the designer but guidelines for this evaluation are available (Borowicka,1936).

Bearing capacity failure of the underlying soils can be verified using conventional geotechnical procedures for a circular foundation, see NAVFAC DM7.2.

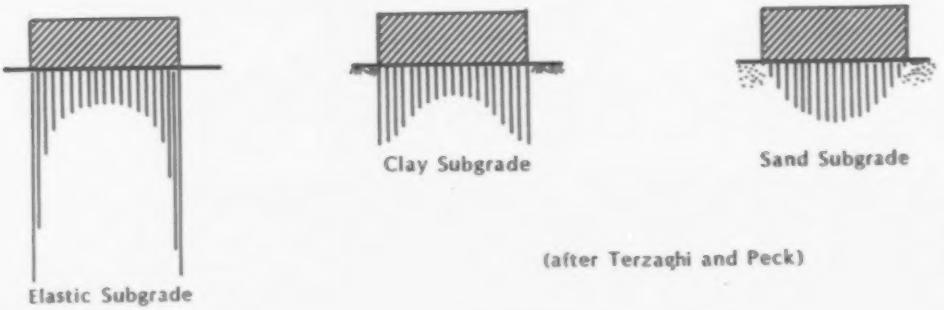
Designs for smaller facilities and surface impoundments frequently run the standpipes up the sideslopes. Both the primary and secondary standpipes can be placed up the sideslopes as shown on Figure 4.8. The use of a synthetic LCR forces the standpipes to disrupt the profile of the FML.

MONITOR for SECONDARY LCR

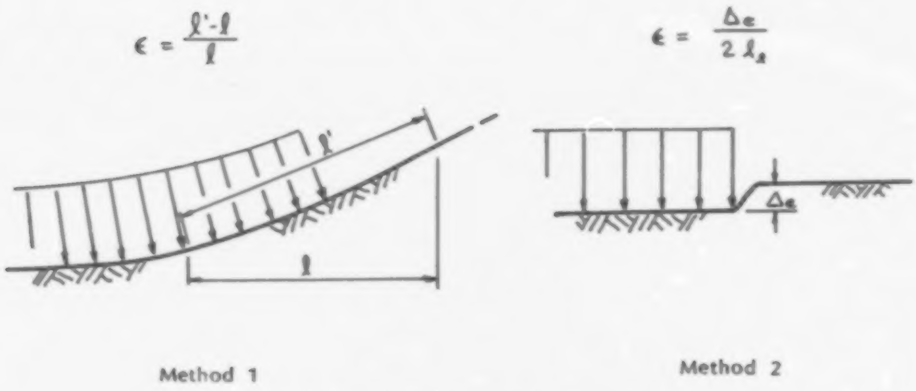
The secondary LCR acts as a witness drain to verify the integrity of the primary FML. The monitoring system for the secondary LCR must allow monitoring, sampling, and the removal of leachate if required. During construction of the facility, the secondary LCR removes surface water from within the cell. This water must be removed by the monitor system. Thus the



A) ELASTIC SETTLEMENT CONSTANT


Clay Subgrade
Sand Subgrade
(after Terzaghi and Peck)
Elastic Subgrade

B) DISTRIBUTION OF CONTACT PRESSURES


$\epsilon = \frac{\ell' - \ell}{\ell}$
$\epsilon = \frac{\Delta_e}{2 \ell_s}$
ℓ'
ℓ
Δ_e
Method 1
Method 2

C) CALCULATION OF FML STRAIN

Figure 4.7 Standpipe Induced Strain in FML

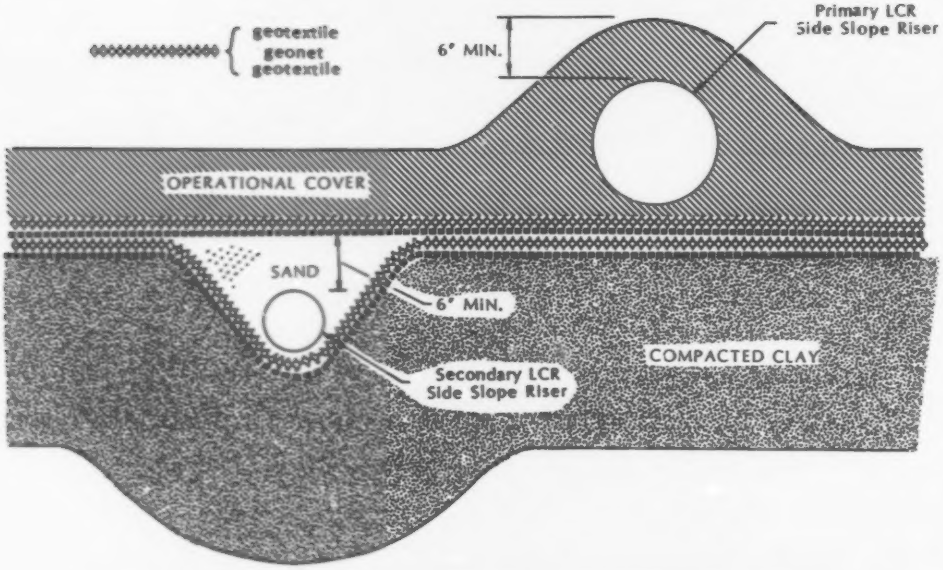
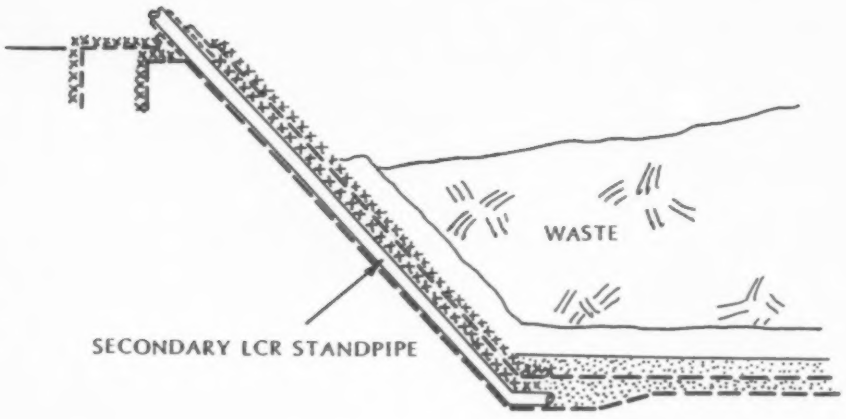


Figure 4.8 Sidewall Standpipe - Detail

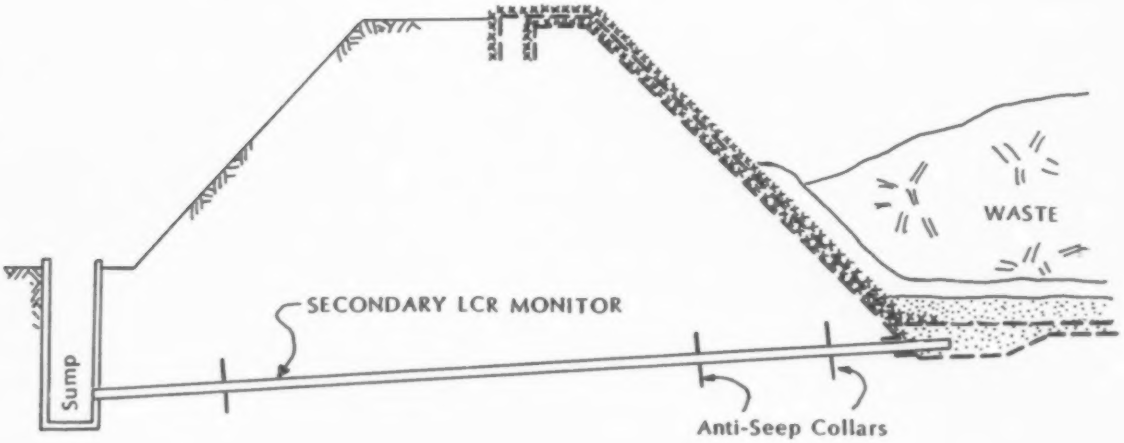
monitor system for the secondary LCR must be capable of more than detection of de minimis quantities of water. At the same time an overly large capacity in this system could lead to a significant lag time in detecting leaks within the primary FML. A vertical standpipe cannot be readily used for this purpose since it would have to penetrate the primary FML. While it is possible to design a secure penetration of the FML, see Section VI, good design practice would require the penetration only as a last resort.

To avoid penetration of the primary FML, the monitor system for below-grade cells must lay within the secondary LCR system and exit the cell by following the slope of the side walls. The minimum pipe diameter is controlled by that required for the monitoring pump and the flow required. Typically a 8 to 10-inch HDPE pipe is used. Generally the secondary LCR must be capable of removing fluids at the same rate as the primary LCR, but the capacity will be obtained using many smaller monitor pipes to replace the large standpipes. Cells using a synthetic secondary LCR will allow only a minimum pipe diameter monitor to be used without providing trenches for the pipe. A typical monitoring system for the secondary LCR system in a below ground cell is shown in Figure 4.9a. The monitoring pipe must pass through the primary FML at some point. In the system shown, the penetration is made at the top of the cell to be above potential leachate. Failure of the seal between the primary FML and the monitor tube at this location will not allow leachate to enter the secondary LCR system. It should be noted that a minimum side slope will make it difficult to place or remove pumps in such monitor pipes.

Monitoring systems for the secondary LCR system in above-grade cells can exit the system horizontally without penetrating the primary FML and yet be accessable for monitoring. Such a system is shown on Figure 4.9b. In most of these systems the pump may be placed within a sump that is external to the cell. Drainage of leachate into the sump is by gravity flow which provides a passive monitoring system for leachate generation. Anti-seep


WASTE
SECONDARY LCR STANDPIPE

A) SECONDARY LCR MONITOR – BELOW GRADE CELL


WASTE
SECONDARY LCR MONITOR
Sump
Anti-Seep Collars

B) SECONDARY LCR MONITOR – ABOVE GRADE CELL

Figure 4.9 Standpipes for Secondary LCR System

collars are typically used on such drainage pipes to prevent the piping of liquid along the outer surface of the pipe. Such collars are typically sized to add at least 10% to the flow length required for such piping. The use of anti-seep collars is currently the subject of concern in small dams due to past problems in obtaining adequate soil compaction around such collars. Many earth dams are currently being constructed without anti-seep collars on embedded pipes. If anti-seep collars are used, then adequate field CQA should be provided to ensure proper soil compaction adjacent to the collar.

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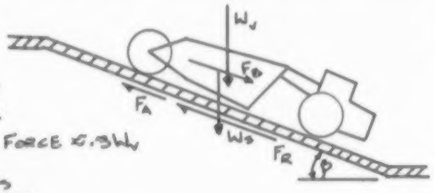
Cell Component: RAMP

Consideration: SLIDING - VERIFY THAT RAMP SUB-BASE IS STABLE UNDER LOAD.

Required Material Properties	Range	Test	Standard
SOIL-LCR FRICTION ANGLE, δ_{SL}	20 - 35°	DIRECT SHEAR	ASTM PROPOSED
SOIL - FML FRICTION ANGLE, δ_{FML}	14 - 22°		
LCR - FML FRICTION ANGLE, δ_{MIN}	10 - 18°		

Draft MTG Minimum

Analysis Procedure:



(1) DEFINE DRIVING FORCES

W_s = WEIGHT OF ROADWAY
W_v = WEIGHT OF VEHICLE
F_B = VEHICLE BRAKING FORCE $\leq .3W_v$

(2) DEFINE RESISTING FORCES

F_R = FRICTIONAL FORCE @ BASE OF ROADWAY
$= (W_v + W_s) * \cos\beta * \tan\delta_{MIN}$

WHERE δ_{MIN} IS THE MINIMUM FRICTIAL INTERFACE ANGLE

F_A = ADHESION FORCE
$= WL * C_{MIN}$ W = RAMP WIDTH L = RAMP LENGTH
WHERE C_{MIN} IS THE MINIMUM INTERFACE ADHESION

(3) DEFINE DESIGN RATIO, DR

$$DR = \frac{\text{RESISTING FORCES}}{\text{DRIVING FORCES}}$$

$$DR = \frac{F_R + F_A}{(W_s + W_v)\sin\beta + F_B} \quad \text{(DYNAMIC w/ } F_B\text{)}$$

Design Ratio:

DR_{MIN} = 3.0 WITH STATIC LOADS
2.0 WITH DYNAMIC LOADS

References:

Example:

GIVEN:

- EQUIPMENT = 55 TON PAN
- FRICTION/ADHESION:

	δ	c	
SOIL-LCR	31°	200 PSF	
SOIL-FML	18°	50 PSF	
FML-LCR	12°	0	← FAILURE CRITERIA

- RAMP GEOMETRY:
  WIDTH = 18' LENGTH = 150' THICKNESS = 24" β = 8°
- RAMP SUBBASE:
  γ = 130 PCF ϕ = 36° c = 1200 PSF

(1) DEFINE DRIVING FORCES

W_s = WEIGHT OF ROADWAY = $150 \times 18 \times \frac{24}{12} \times 130$ = 702000 lbs = 702 KIP
W_v - VEHICLE WEIGHT = 55 TON = 110 KIP
F_B = BRAKING FORCE = .3 * 110 KIP = 33 KIP

(2) DEFINE RESISTING FORCES

δ_{MIN} = 12° $C_{MIN} = 0 \rightarrow F_A = 0$

$F_R = (702 + 110) * \cos 8° * \tan 12°$
= 170.9 KIPS

(3) DEFINE DESIGN RATIOS, DR

$$DR_{STATIC} = \frac{170.9}{(702 + 110)\sin 8°} = \frac{170.9}{113} = 1.51 \quad \text{NG}$$

$$DR_{DYNAM} = \frac{170.9}{113 + 33} = \frac{170.9}{146} = 1.17 \quad \text{NG}$$

RECOMMEND PLACING SMALL LAYER OF SAND BETWEEN LCR AND FML TO INCREASE FRICTION ANGLE δ_{MIN}

Example No. 4.1

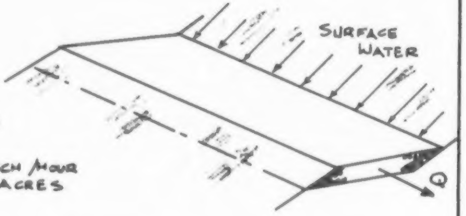
Cell Component: RAMP

Consideration: DRAINAGE: VERIFY THAT RAMP WILL ADEQUATELY DRAIN SURFACE WATER FROM ROADWAY.

Required Material Properties	Range	Test	Standard
• IN-PLANE FLOW OF LCR, θ	10^{-2} CM/SEC*	TRANSMISSIVITY	ASTM D4617
• PERMEABILITY, K, OF SUBBASE	10^{-2} - 10^{-4} CM/SEC	PERMEABILITY	ASTM D2434

*Draft MTG Minimum

Analysis Procedure:



(1) ESTIMATE FLOW RATE, Q

$Q = C I A_{ws}$ (FT³/SEC)

WHERE $C = 1.0$

I = RAINFALL, INCH/HOUR

A_{ws} = WATERSHED, ACRES

(2) ESTIMATE FLOW CAPACITY OF LCR + ROADWAY Q_{ACT}

$Q_{ACT} = Q_{ROAD} + Q_{LCR}$

WHERE $Q_{ROAD} = K i A$ A = AREA, i = GRADIENT = TANGENT OF SLOPE

$Q_{LCR} = \theta i W$ W = WIDTH OF LCR

(3) CALCULATE DESIGN RATIO, DR

$$DR = \frac{\text{FLOW CAPACITY}}{\text{FLOW RATE}} = \frac{Q_{ACT}}{Q}$$

Design Ratio:

$DR_{MIN} > 1.5$

References:

Example:

GIVEN:

• RAMP PARAMETERS: WIDTH = 18' THICKNESS = 2'-0"

$K = 1 \times 10^{-2}$ CM/SEC = 3.3×10^{-4} FT/SEC

SLOPE, $\beta = 8° \rightarrow i = \tan 8° = 0.14$

• SURFACE WATER: A_{ws} = WATERSHED = .4 ACRES

I = RAINFALL = 3 IN/HOUR

• PRIMARY LCR: $\theta = 3 \times 10^{-5}$ M²/SEC = 32.3×10^{-5} FT³/SEC

(1) ESTIMATE FLOW RATE, Q

$Q = C I A_{ws}$

$= 1 * 3 * .4 = \underline{\underline{1.2}}$ FT³/SEC

(2) ESTIMATE FLOW CAPACITY OF LCR + ROADWAY

$Q_{LCR} = \theta i W$

$= 32.3 \times 10^{-5} * 0.14 * 18$

$= 8.14 \times 10^{-4}$ FT³/SEC

$Q_{ROAD} = K i A$

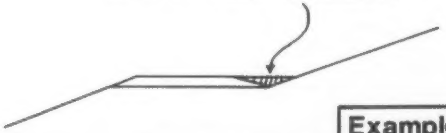
$= 3.3 \times 10^{-4} * 0.14 * 18 * 2$

$= 1.65 \times 10^{-3}$ FT³/SEC

(3) CALCULATE DESIGN RATIO, DR

$$DR = \frac{Q_{LCR} + Q_{ROAD}}{Q} = \frac{1.65 \times 10^{-3} + 8.14 \times 10^{-4}}{1.2} = 2 \times 10^{-3} \quad \underline{\underline{NG}}$$

RECOMMEND: FLOW CAPACITY WITHIN ROADWAY IS INSUFFICIENT, THEREFORE PROVIDE SURFACE FLOW CHANNEL



Example No. 4.2

Cell Component: RAMP

Consideration: WHEEL LOADING - VERIFY THAT WHEEL LOADING WILL NOT DAMAGE FML.

Required Material Properties	Range	Test	Standard
FML COMPRESSIVE STRENGTH σ		COMPRESSION	
ROADWAY SUBBASE FRICTION ANGLE ϕ	25 - 40°	TRIAXIAL	ASTM PROPOSED

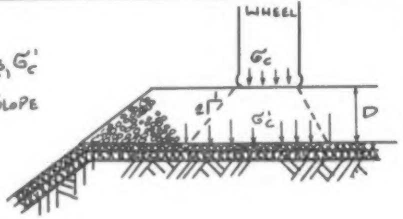
Draft MTG Minimum

Analysis Procedure:

(1) DEFINE FIELD CONTACT STRESS, σ'_c

ASSUMING 2:1 DISTRIBUTION SLOPE

$$\sigma'_c = \sigma_c * \left[\frac{R^2}{(R+D)^2}\right]$$



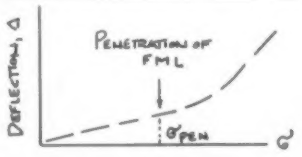
WHERE D = ROADWAY THICKNESS

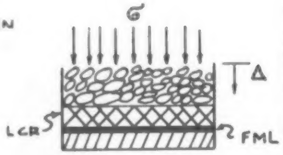
R = EFFECTIVE RADIUS OF TIRE CONTACT $= [P/\pi\,\sigma_c]^{1/2}$

P = AXLE LOAD

σ_c = TIRE CONTACT PRESSURE

(2) MEASURE FML COMPRESSIVE STRENGTH, σ_{PEN}





(3) DEFINE DESIGN RATIO DR

$$DR = \frac{\text{COMP STRENGTH}}{\text{CONTACT STRESS}} = \frac{\sigma_{PEN}}{\sigma'_c}$$

Design Ratio:

DR_{MIN} 3.0 @ 10% PENETRATION

References:

BOWLES (1977)

Example:

GIVEN:

- WHEEL LOADING
  - 55 TON PAN w/ 4 WHEELS ➔ 27.5 KIP WHEEL LOAD
  - GROUND CONTACT PRESSURE = 55 psi
- ROADWAY
  - THICKNESS, D = 2'-0"

(1) DEFINE FIELD CONTACT STRESS, σ_c

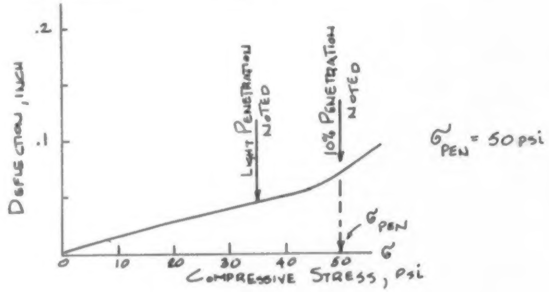
R = EFFECTIVE RADIUS = $[27500/\pi \times 55]^{1/2}$ = 12.6 INCH

D = THICKNESS = 2' = 24"

$$\sigma'_c = 55 = \left[\frac{12.6^2}{(12.6+24)^2}\right]$$

$$\sigma'_c = 6.5 \text{ psi}$$

(2) MEASURE FML COMPRESSIVE STRENGTH, σ_{PEN}



σ_{PEN} = 50 psi

(3) DEFINE DESIGN RATIO, DR

$$DR = \frac{\sigma_{PEN}}{\sigma'_c} = \frac{50}{6.5} = \underline{\underline{7.7}}$$

Example No. 4.3

Cell Component: STANDPIPE

Consideration: DOWN-DRAG: EVALUATE POTENTIAL DOWN-DRAG FORCES ACTING ON STANDPIPE AND COMPARE COATINGS FOR REDUCTION OF THESE FORCES

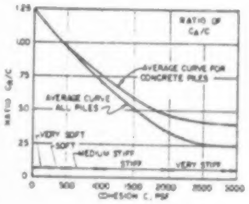
Required Material Properties	Range	Test	Standard
COHESION OF CLAY FILL		TRIAXIAL	ASTM PROPOSED

Draft MIG Minimum

Analysis Procedure:

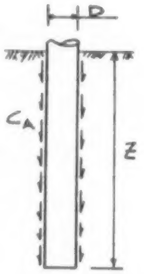
(1) STANDPIPE DOWNDRAG WITHOUT COATING

$$Q_{DRAG} = C_A \pi D Z$$



RECOMMENDED VALUES OF ADHESION

PILE TYPE	CONSISTENCY OF SOIL	COHESION, C PSF	ADHESION, C_A PSF
TIMBER AND CONCRETE	VERY SOFT	0 - 250	0 - 250
	SOFT	250 - 500	250 - 480
	MED. STIFF	500 - 1000	480 - 750
	STIFF	1000 - 2000	750 - 950
	VERY STIFF	2000 - 4000	950 - 1300
STEEL	VERY SOFT	0 - 250	0 - 250
	SOFT	250 - 500	250 - 460
	MED. STIFF	500 - 1000	460 - 700
	STIFF	1000 - 2000	700 - 720
	VERY STIFF	2000 - 4000	720 - 750



(NAVFAC DM7.2)

OBTAIN C_A FROM ABOVE DATA

(2) STANDPIPE DOWNDRAG WITH BITUMEN COATING

ASSUMING REDUCTION FACTOR = 6

$$\bar{Q}_{DRAG} = Q_{DRAG}/6$$

Design Ratio:

NOT APPLICABLE

References:

VESIC (1977)

NAVFAC DM 7.2 (1982)

Example:

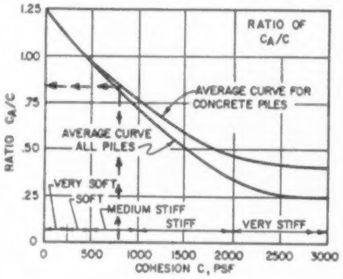
GIVEN:

- STANDPIPE (RCP)
  - DIAMETER, D = 48"
  - DEPTH, Z = 65'
- CLAY BACKFILL
  - COHESION = 800 PSF (MEDIUM STIFF)

(1) STANDPIPE DOWNDRAG WITHOUT COATING

RATIO $C_A/C = 0.85$

$\rightarrow C_A = .85 \times 800 = 680$ PSF



$Q_{DRAG} = 680 \times \pi \times 4 \times 65$

$= 555000$ lb

$= \underline{\underline{555}}$ KIPS

(2) STANDPIPE DOWNDRAG WITH COATING

$\bar{Q}_{DRAG} = 555/6$

$= \underline{\underline{92.5}}$ KIPS

Example No. 4.4

Cell Component: STANDPIPE

Consideration: PUNCTURE OF FML: VERIFY THAT DOWN-DRAG INDUCED SETTLEMENT OF STANDPIPE WILL NOT CAUSE FAILURE OF UNDERLYING LCR.

Required Material Properties	Range	Test	Standard
CLAY SUBGRADE:			
• COHESION, C	.5-5 TSF	TRIAXIAL	ASTM PROPOSED
• POISSON'S RATIO, ν	.3-.45	"	
• COMPRESSION INDEX, C_c	<0.3	CONSOLIDATION	ASTM 2435
FML RELATED:			
• FML/SOIL FRICTION ANGLE, δ	10-20°	DIRECT SHEAR	ASTM PROPOSED
• FML STRAIN-AT-YIELD	10-20%		

Draft MTG Minimum

Analysis Procedure:

(1) CALCULATE ELASTIC SETTLEMENT COMPONENT, Δ_{EL}

$$\Delta_{EL} = \frac{Pa}{E}(1-\nu^2)K \qquad Eq(4.1)$$

P = AVERAGE CONTACT PRESSURE
a = RADIUS
E = SUBGRADE MODULUS ≈ 600c
ν = POISSON'S RATIO
K = CONSTANT - SEE FIG. 4.7

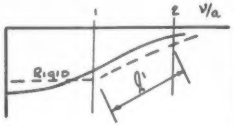
(2) CALCULATE CONSOLIDATION SETTLEMENT COMPONENT, Δ_{CON}

$$\Delta_{CON} = H * \left(\frac{\Delta e}{1+e_0}\right)^*$$

H = THICKNESS OF UNDERLYING CLAY LAYER
e_0 = INITIAL VOID RATIO OF CLAY
$\Delta e = C_c \, \Delta \log P$
C_c = COMPRESSION INDEX
ΔP = CHANGE IN NORMAL STRESS

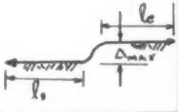
(3) ESTIMATE STRAIN - METHOD 1 (FIG 4.7c)

- ESTABLISH SETTLEMENT PROFILE PER FIG 4.7a
  - $\Delta_{MAX} = \Delta_{EL} + \Delta_{CON}$ @ r/a = 0
  - CALC ℓ' TO r/a = 1.6
- STRAIN, $\epsilon = (\ell' - \ell)/\ell$ WHERE $\ell = 2a$



(4) ESTIMATE STRAIN- METHOD 2 (FIG 4.7c)

- SOLVE FOR EFFECTIVE FML LENGTH, ℓ_e (EQ 3.17)
- STRAIN, $\epsilon = \Delta_{MAX} / 2\ell_e$



(5) CALCULATE DESIGN RATIOS

$$DR = \frac{\epsilon_{YLD}}{\epsilon}$$

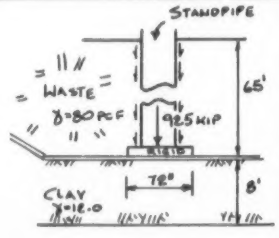
Design Ratio:

$DR_{MIN} > 2.0$ ON YIELD

References:

* SEE SOIL MECHANIC'S TEXTS

Example:



- STANDPIPE PER EXAMPLE 4.4
- CLAY SUBGRADE
  - INITIAL VOID RATIO, e_0 = 0.3
  - COHESION = 1800 PSF
  - POISSON'S RATIO = 0.35
  - COMPRESSION INDEX 0.05
- FML → f_Y = 2200 psi, d = 60 mil ϵ_{YLD} 12%
  $\delta_{FML\text{-}SOIL}$ = 15°

(1) CALCULATE ELASTIC SETTLEMENT COMPONENT Δ_{EL}

$$\Delta_{EL} = \frac{3.27(1-.35^2)}{1080} 1.6 \approx \underline{.05 \text{ INCH}}$$

$P = 92.5/(\pi \times 3^2) = 3.27$ KSF
$E = 600 * 1.8$ KSF = 1080 KSF
K = 1.6 @ CENTER

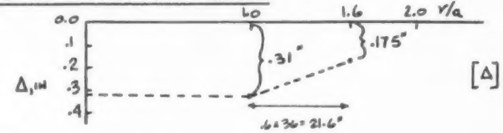
(2) CALCULATE CONSOLIDATION SETTLEMENT COMPONENT, Δ_{CON}

$$\Delta_{CON} = 8*12\left(\frac{.0036}{1+0.3}\right) = \underline{0.26 \text{ INCH}}$$

$\Delta e = 0.05 * \log \frac{P_f}{P_i} = .0036$
P_f = FINAL OVERBURDEN PRESS.
$= 65 \times 80 + 4 \times 120 = 5680$ PSF
P_i = INITIAL OVERBURDEN PRESS
$= 40 \times 120 = 4800$ PSF
(ASSUMES 40' EXCAVATION)

(3) ESTIMATE STRAIN - METHOD 1

ESTABLISH SETTLEMENT PROFILE



$$[\Delta]_{r/a=2.0} = \frac{.9}{1.6} \times 0.31 = .175"$$

STRAIN

$$\epsilon = \frac{\ell' - \ell}{\ell'} \quad \text{BUT} \quad \ell' = \sqrt{21.6^2 + .14^2} = 21.6 \Rightarrow \underline{\epsilon \approx 0\%}$$

(4) ESTIMATE STRAIN - METHOD 2

SOLVE FOR ℓ_e, EQ (3.17)

$$\ell_e = [2200 * .06] / [2 \times 361 * \tan 15°] = 6.8 \text{ INCH}$$

A: 65×80 = 5200 psf
= 36.1 psi

STRAIN

$$\epsilon = \frac{0.31}{2 \times 6.8} = \underline{2.3\%}$$

(5) CALCULATE DESIGN RATIOS

$$DR_1 = \frac{12}{\approx 0} > \text{VERY HIGH}$$

$$DR_2 = \frac{12}{2.3} = 5.2 \quad \underline{OK}$$

Example No. 4.5

SECTION V

DESIGN OF COMPONENTS ABOVE CELL

An important aspect of the liquids management program strategy behind EPA's statutory design is the minimization of leachate generation from the infiltration of surface water into the cell. To prevent this infiltration, the landfill must be sealed or capped after the cell is filled. The regulatory requirements (40 CFR 264.310) specify that final cover be designed and constructed to:

(1) Provide long-term minimization of migration of liquids through the closed landfill.

(2) Function with minimum maintenance.

(3) Promote drainage and minimize erosion or abrasion of the cover.

(4) Accommodate settling and subsidence so that the cover's integrity is maintained.

(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

Recommended guidance has been developed for meeting these five regulatory requirements (EPA, 1982). Although alternative designs could also meet the five regulatory requirements, the ability of alternative designs would have to be demonstrated with more detail than the recommended design.

RCRA guidance (EPA,1986) for covers at uncontrolled hazardous waste sites specifies that the cover should consist of the following as minimum: protective top cover, middle drainage layer, and low permeability bottom layer consisting of an optional 20 mil synthetic upper component and a 2 ft. clay layer lower component. Some states have slightly different cell cap profiles based on local conditions. For example, New York currently requires a cover system that includes, from the waste outward, a final operations cover (12 in minimum), three feet of compacted clay, a 40 mil HDPE geomembrane, 18-inches of vegetative cover, and 6-inches of topsoil. The drainage layer is not included and is felt to pose a hazard to the vegetative cover. Commentary in the Second MTG document on Double Liners systems indicates that EPA does not require that facilities using double FMLs to also use two flexible membrane caps (FMC).

The design cross-section of the minimum RCRA cover is shown on Figure 1.4. The upper layer of the cell cover system is a protective top cover composed of vegetative and topsoil components. The protective top cover is designed and constructed to prevent erosion and abrasion of the underlying cover components, while functioning with minimum maintenance. A vegetative layer forms the upper surface of the protective surface layer and functions to reduce percolation into the cover system, shield the topsoil from raindrop impact, stabilize the soil against the erosive and abrasive forces of wind and water, bind and anchor the soil to form a stable mass, increase evaporation rates, and enhance the aesthetics of the site.

Selection of the vegetation species is an important consideration in design of the cover and is dependent upon factors such as climate, site characteristics, and soil properties. The vegetation must be both persistent and not have roots that might penetrate beyond the upper protective layer. References which provide discussions on available plants and site selection criteria include EPA (1979), EPA (1983), and Lee, et al. (1985). In some regions of the country, such as arid and semi-arid climates, establishment of a vegetative cover is difficult or impossible. In these areas, a rock or gravel mulch layer of approximately 5 to 10 centimeters in thickness may be substituted for the vegetation (Cline,1979).

The topsoil forming the protective top cover must be selected and constructed to support the vegetation by allowing sufficient surface water to infiltrate into the topsoil and by retaining enough plant-available water to sustain plant growth through drought periods. Particle size distribution, structure, and organic matter content influence the quantity of available water a given soil can supply and should be considered in selecting the topsoil material. The mimimum recommended topsoil thickness is 60 centimeters (24 inches); however, some geographic regions may require a thicker layer to provide adequate plant available water. In general, medium-textured soils, such as loam soils, have the best overall characteristics for seed germination and plant root system development.

The cell cover system includes a drainage layer located below the protective surface layer and immediately above the membrane component of the hydraulic barrier. This drainage layer must intercept and drain percolating water to prevent it from standing on the hydraulic barrier. The percolating water follows a downward migration path until the hydraulic barrier layer is reached; it then flows horizontally under the force of gravity through the drainage medium to an outlet at the perimeter of the cover. A minimum drainage layer thickness of 30 cm (12 in) and a minimum hydraulic conductivity of $1x10^{-2}$ cm/sec are recommended. The bottom slope of the drainage media must be more than 2% after allowance for settlement. The layer may be constructed of granular drainage material classified by the Unified Soil Classification System (USCS) as SP (poorly graded sand) or synthetic drainage systems, such as geonets and geocomposites.

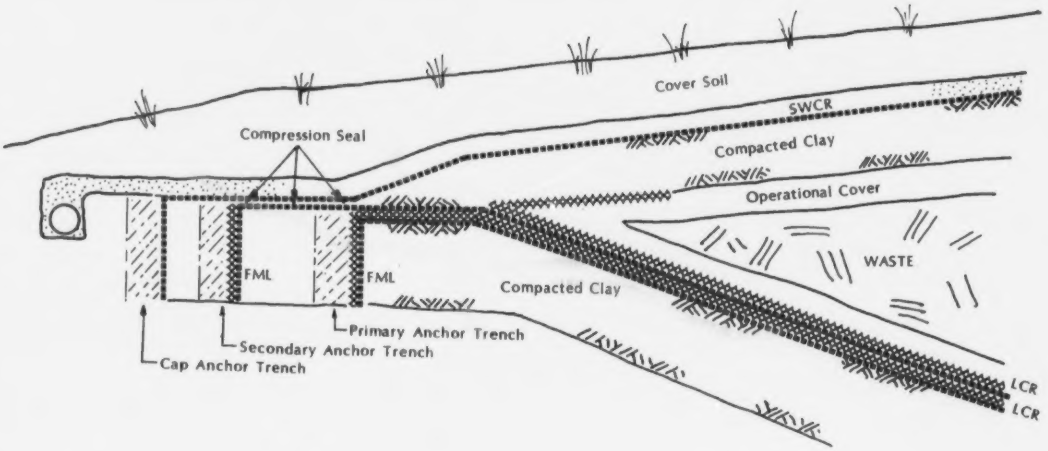
The hydraulic barrier layer of the final cover system consists of two components: 1) a compacted soil component having a minimum field hydraulic conductivity of $1x10^{-7}$ cm/sec; overlain by 2) a flexible membrane cap (FMC). The FMC is placed in direct contact with the clay soil and a compression seal is created by the overburden; thus the two components form a composite barrier to the flow of percolating liquid. The recommended minimum thicknesses of the two components are 60 centimeters (24 inches) for the compacted soil and 20 mils (0.5 millimeters) for the FMC. The actual thicknesses are based upon characteristics of the site, soil, synthetic material, and expected external forces, such as settlement and overburden pressures. Construction of the compacted soil component and installation of the FMC are analogous to the practices used in liner construction, discussed in Section III. Techniques similar to these, along with appropriate CQA procedures, should be employed in construction of the hydraulic barrier. Additional recommendations on barrier design and construction are given in EPA (1986b), and information on development of a CQA program is given by EPA (1986a).

The FMC component of the hydraulic barrier is placed directly above the compacted soil component and immediately below the drainage layer. The compacted soil will, therefore, act as a buffer and foundation for the FMC, and the drainage layer will provide protection from overlying materials. The drainage layer should be inspected for materials which may damage or otherwise impair the synthetic FMC. Care must be taken to provide adequate protection against damage to the FMC by equipment or personnel during placement of the drainage layer. When possible, the FMC must be placed wholly beneath the maxiumum frost depth at the facility site. Appropriate CQA procedures, as discussed in Section VI, should also be maintained to ensure the integrity of the FMC installation.

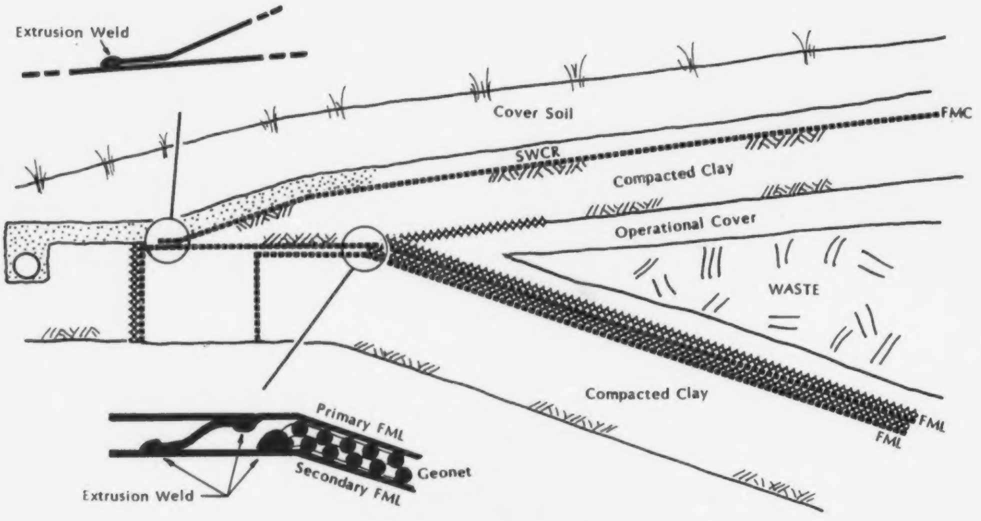
In a modern hazardous waste landfill, the compacted clay layer is constructed upon a compacted layer of protective soil that provides a uniform foundation or bench for construction of the cap. A gas collection system is not typically needed in a hazardous waste landfill due to the solidification of all waste and the absence of organic matter. However, if required, the collection system is placed either above or beneath this compacted clay layer. The gas collection system must be designed to both handle the estimated volume of gas generated and to remain serviceable under the projected long term settlement of the cap.

The design geometry of the cap is controlled by the need to move surface waters away from the cell even after long term settlements have occurred. Because the random bulk of the contained waste prevents good compaction, significant settlements of the cap are possible. Poorly compacted cells and those containing free sludge wastes require stabilization of the waste prior to capping. Excessive settlements of the waste can produce localized depressions that allow surface water to pond and remain in contact with the FMC for a prolonged period of time. Additionally, this settlement can produce significant strains within the cap that threaten the physical integrity of the components that form the cap. Initial design contours of the cap must therefore be sufficient to ensure that positive drainage remains through the entire life of the cell, but not so large that surface erosion is fostered on the initial profile.

The RCRA cap shown on Figure 1.4 is more frequently required to interface with cell systems that use synthetic LCR systems on the sidewalls. A RCRA cap utilizing synthetic LCR systems is shown on Figure 5.1a. In both systems it is important that surface water be prevented from entering either the waste or the LCR systems. This requires that the clay component of the cap hydraulic barrier must form a compression seal with the primary FML and that the LCR systems be isolated from the cap. To provide for this seal, the primary LCR will not be able to be anchored in common with the primary FML or it may be necessary to remove that portion of it that lies between the primary FML and the clay layer of the cap's hydraulic barrier prior to placement of the clay layer. For the cell shown on Figure 5.1a, the synthetic primary LCR was cut free at its anchorage trench and folded over the protective soil cover. This would obviously occur after the waste is in-place; at which time the anchor trench is not serving a function. The clay layer of the cap would then be in direct contact with the primary FML. The FMC is placed in a trench at the


Cover Soil
SWCR
Compression Seal
Compacted Clay
Operational Cover
WASTE
FML
FML
Compacted Clay
Primary Anchor Trench
Secondary Anchor Trench
Cap Anchor Trench
LCR
LCR

A) Geosynthetic RCRA Cell Profile


Extrusion Weld
Cover Soil
FMC
SWCR
Compacted Clay
Operational Cover
WASTE
Compacted Clay
FML
FML
Primary FML
Geonet
Secondary FML
Extrusion Weld

B) "Sealed" Geosynthetic Cell Profile

Figure 5.1 Geosynthetics in RCRA Double FML Cell Profile

perimeter of the cap to guard against erosional undercutting of the cap.

An alternative cap design is shown in Figure 5.1b which provides welded sealing of the secondary LCR system and of the FMC to the primary LCR. This 'total containment' design would be appropriate at sites having high water tables or suffering from frequent flooding. Such sites are obviously marginal but may be in existence under interim permit status. The seaming of the FMC to the cap is not desireable if settlements within the waste are anticipated. Such settlements could lead to failure of the seams and tearing of the primary FML. For this reason, the alternate design is not recommended.

A double drainage layer-FMC system may be appropriate for facilities that are projected to experience significant settlements of the cap or be exposed to severe environmental forces. The double drainage layer-FMC profile would be the same as that shown on Figure 5.1a with two layers of FMC and SWCR. The details for such a cap are very tedious to design and even more so to construct. Yet, they are absolutely essential to the proper, long-term performance of the waste facility.

SURFACE WATER COLLECTION/REMOVAL

The Surface Water Collection/Removal (SWCR) system is immediately above the FMC and functions to drain surface waters away from the FMC and to provide a protective bedding material for the FMC. Current MTG recommendations provide for the use of a synthetic SWCR system if it can be demonstrated that it will provide protection equivalent to that provided by the conventional use of a 12-inch layer of sand. To demonstrate that the synthetic SWCR can be used as a bedding material, it must be shown that the SWCR will not exhibit brittle failure under the stresses from overburden and equipment used for construction. The SWCR system must be designed so that it has hydraulic properties sufficient to quickly remove collected surface water, filtration characteristics that prevent clogging of the drain due to infiltration of the soil, and adequate strength to prevent damage to the system during installation or from service loads. On double FMC caps the witness drain placed between the FMCs is designed in an identical manner except filtration characteristics are not important.

SWCR Transmissivity

A geosynthetic system used to replace the granular bedding layer on top of the FMC must provide sufficient planar flow capacity to prevent surface water from accumulating and standing on the FMC. Unlike the LCR systems, no maximum head is currently specified by statute or MTG criteria. In that the FMC must have a permeability equal to or less than the thickest FML, it would seem reasonable to design the FMC for a maximum tolerable surface water head of 1 foot. The design amount of water entering the system would therefore roughly equal the amount of leachate passing through the liner system. Using properties suggested in the RCRA guidance, a 12 inch layer with a saturated hydraulic conductivity of not less than 10^{-3} cm/sec, the minimum transmissivity of the SWCR layer is 3×10^{-6} m^2/s.

The transmissivity of a geosynthetic is influenced by the flow gradient, the normal load on the system, and the long-term creep

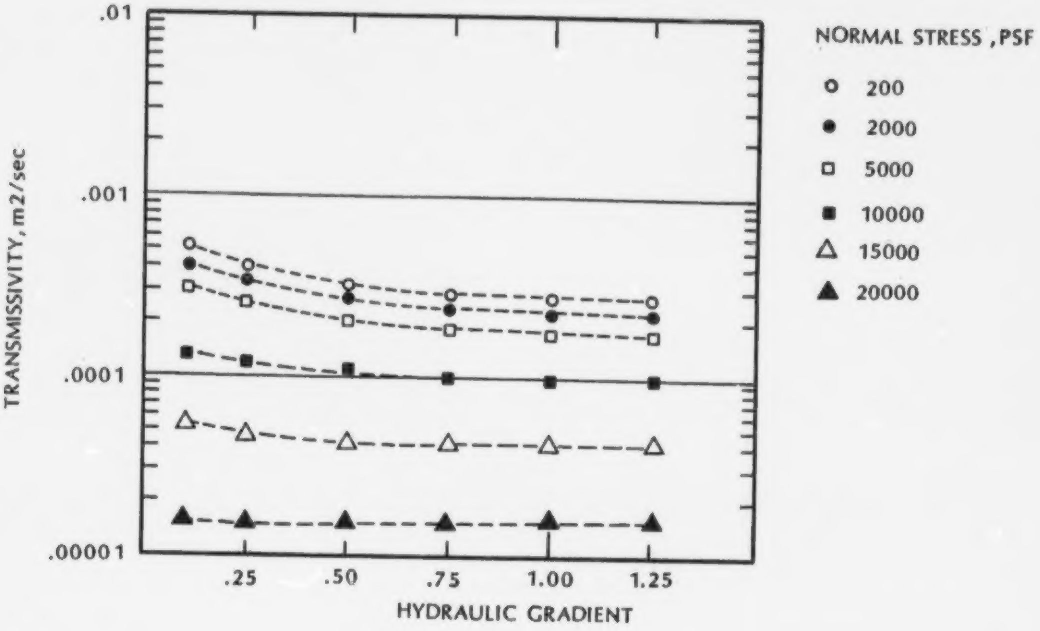


Figure 5.2 Transmissivity Data for a Needled Nonwoven Geotextile

compressibility characteristics of the geosynthetic. These properties must be evaluated in the laboratory. Typical laboratory curves for the short-term performance of a geosynthetic drain are shown on Figure 5.2 for hydraulic gradients less than 1.0. Example 5.1 presents the design calculations used to evaluate the planar flow capacity of a given geosynthetic drainage system. The design is based on a maximum head acting on the SWCR of 1 foot. Because of the small normal stress, the long-term creep of materials used for the surface water collection system rarely influences the design. Long-term performance of the SWCR system is evaluated using the same procedure as previously shown for LCR systems in Example 3.3.

SWCR Filtration

The SWCR system must incorporate a properly designed filter fabric into its surface that is adjacent to the cover soil. This fabric must be selected to allow the flow of water, yet prevent the movement of soil fines into the core of the SWRC. Filter criteria are based on grain size empirical relationships and the gradient-ratio test discussed in Section III and are demonstrated in Examples 3.5 and 3.6. These criteria are also applicable to the selection of a filter material for the SWCR system. An alternate laboratory filtration test proposed by Koerner and Ko (1982) is also shown in Example 3.5 for evaluating the clogging potential of the SWCR. This test places a sample of the cover soil against the SWCR system and monitors the flow of water through the system over time. Qualification of the SWCR in this test is based on both the flow reaching a steady-state condition and the flow rate being sufficient.

SWCR Strength

The SWCR system must be analyzed to ensure that shear failures do not occur at the surface or interior boundaries and that strains caused by settlement or low shear capacity will not lead to rupture of the system. The slope of the cover will range from the minimim of 2 degrees required for the gas collection system to a maximum of 3:1 (18.4 degrees) that is the limit for mechanized mowing of a slope. Typical cover slopes will be in the range of 5 to 8 degrees. Cover soil placed on the SWCR system will want to slide down the slope and its stability must be verified. The friction angle between the cover soil and the surface of the SWCR should be evaluated in the laboratory under saturated conditions. This angle is influenced by the physical properties of the cover soil and the surface geotextile of the SWCR system. The extreme design condition will occur when the cover soil is saturated and the SWCR system has the full design head acting on it. Example 5.2 demonstrates the calculations used to establish the stability of the cover soil.

The shear stresses transferred into the SWCR by the cover soil must not exceed the shear strength of the SWCR itself. The shear calculations presented in Example 5.2 model the transfer of shear forces to the surface of the SWCR. Typically, the friction angle between the SWCR and the FMC is significantly less than that between the cover soil and the SWCR. Thus it is possible to transfer more shear stress into the SWCR that can be transferred from the SWCR to the FMC. The difference must be taken by the SWCR in the form of tensile stresses. Example 5.3 demonstrates the calculation of the magnitude of tensile force that can be transferred into the SWCR. Note that the tensile strength of many SWCR systems has not been formalized to date. These tension forces can be reduced by lowering the slope, placing a thinner layer of cover soil, or by increasing the frictional bond between the FMC and the SWCR. This process of evaluating shear stresses at each layer interface must be continued through the entire profile of the cap.

Significant strains can be generated in the SWCR if settlement of the waste occurs. However, the straining of the SWCR in a settlement depression will not lead to a catastrophic failure of the cap. Water will continue to flow around or through the settlement zone, albeit at smaller rates. Evaluation of settlement-induced strains is more critical for the FMC systems. This strain evaluation procedure is given on Figure 3.5 and is the same for both FMC and the SWCR. The calculation of settlement-induced strains is demonstrated in Example 5.4.

FLEXIBLE MEMBRANE CAP

The FMC functions in the same manner as an FML, but under different design conditions. The most significant design differences between the FMC and a FML are as follows:

1) FMC systems will be exposed to surface water infiltration so that chemical compatibility is not of concern.

2) FMC systems may lie within the frost zone in northern regions and thus may be exposed to more significant temperature ranges.

3) Surface settlement may lead to large strains in an FMC during its service life.

4) FMCs typically experience their largest physical strain during post-closure when the cap is in place and not during construction or operation.

5) FMC systems must be designed to provide for venting of gases generated within the cell and are therefore subject to more designed penetrations.

6) The simplified geometry of the FMC results in an easier installation than that required for FML systems.

7) Because of their shallow depth, FMC systems are more prone to damage from burrowing rodents and roots and other long-term problems discussed in Section VII.

Thus while both the FMC and FML systems perform identical functions, the design criteria for selection of the two membrane systems and details are significantly different. The FMC is impacted by the FML design only by the MTG requirement that the permeability of the FMC must be less than or equal to that of the thicker FML or the underlying subgrade. In some states having a authorized RCRA program, this has been interpreted to mean that the FMC is the same material and thickness as the primary FML. This is not the intent of the guidance and is not assumed in this document (Landreth, 1987).

The selection of minimum FML thickness and the design of LCR systems in the liners were controlled by the statutory requirement to maintain less than a 12-inch head of leachate acting on the FML with no more than de minimis leakage through the FML. While no direct statutory or MTG requirement exists for design of the cap, the 12-inch head is assumed to be applicable to the design of cap membranes and drainage features. De Minimis flow through the FMC is not applicable.

FMC Permeability

The permeability of most common polymeric membranes is sufficiently low so that it cannot be evaluated using conventional permeability testing procedures. The flow rates through conventional fixed or falling-head permeameters would be so small that either evaporation would destroy the leakage or extremely high gradients would be required to produce measurable flows. A psuedo permeability of these materials can, however, be measured using a water vapor transmission test (WVT), ASTM E96. The WVT test requires the use of a controlled temperature and humidity test chamber. Details of this test are presented in Section III and in the appendix.

Under draft MTG (EPA, 1986), the lower permeability layer of the cap must provide a permeability less than that of either of the liners underlying the cell. This document is developed assuming that the FMC is not necessarily of the same polymer as the FML. No attempt is made to compare the psuedo permeabilities of the membranes based on WVT data. Chemical compatibility requirements are assumed to be inapplicable to the selection of an FMC polymer. No data exists which shows that the FMC will be exposed to vapors other than carbon dioxide or methane arising from the underlying hazardous waste. Indeed, with a properly installed gas collection system, the FMC should not be exposed to vapors from the waste.

FMC Stresses

Stresses introduced to the membrane during its service life are caused by differential settlements of the waste below the cap. These differential settlements are caused by non-uniform settlements of individual cells within the facility. The amount of strain generated within the membrane is influenced by the breadth and depth of the settlement feature. Figure 3.5 presents the average strain generated within the membrane using simple plane strain circular and triangular settlement models. These simple models were presented by Knipschield (1985) to represent settlement due to improperly backfilled pipe trenches or similar linear features. As the width of the settlement feature becomes large, the average strain in the FMC becomes quite small.

Settlement features in the cap are caused by settlement within the underlying waste. These features will not necessarily be linear like that generated by a pipeline trench. The average radial strain generated in a spherical settlement feature is the same as given in Figure 3.5 for the plane strain mode. The transverse strains, those normal to the radial strain, vary from zero at the surface to a strain equal to the radial strain at the full settlement depth. The existence of significant biaxial tensions in the FMC is important. Biaxial tension tests reported by Steffen (1985) and Gluck (1985) show a dramatic reduction in the strain at failure of HDPE subjected to biaxial tension. Stress-strain curves for HDPE, LDPE, and PVC under uniaxial and biaxial tension are shown on Figure 5.3. The uniaxial strain at rupture for HDPE is typically in excess of 600%. Under biaxial tension, the strain at rupture has dropped to slightly more than 20%. Biaxial strain conditions and strains of 20% are reasonable expectations for FMCs experiencing significant settlement. The strain at rupture for FMC components should be known and specified to avoid FMC failure due to settlement. Design Example 5.4 demonstrates the calculations required to verify the performance of the FMC given a known settlement geometry. Estimating the amount of settlement for use in this procedure remains the major uncertainty. Procedures for estimating settlement geometry are reviewed by others (EPA, 1987).

That portion of the weight of the overlying soil carried by the FMC as the settlement feature is generated can be shown to be quite small in comparison to the total weight of the soil. The total vertical load being carried by the FMC is obtained by summing the vertical component of the FMC stress acting at the edge of the settlement feature. Comparison of the total vertical load on top of the FMC with that carried by the FMC clearly show that the FMC is not a major load carrying component. For circular settlement features, the FMC will carry a greater, though still minor, percentage of the overlying soil load. Thus, the most important load-elongation feature for an FMC is not its modulus but rather its ability to strain biaxially or under confinement without failing.

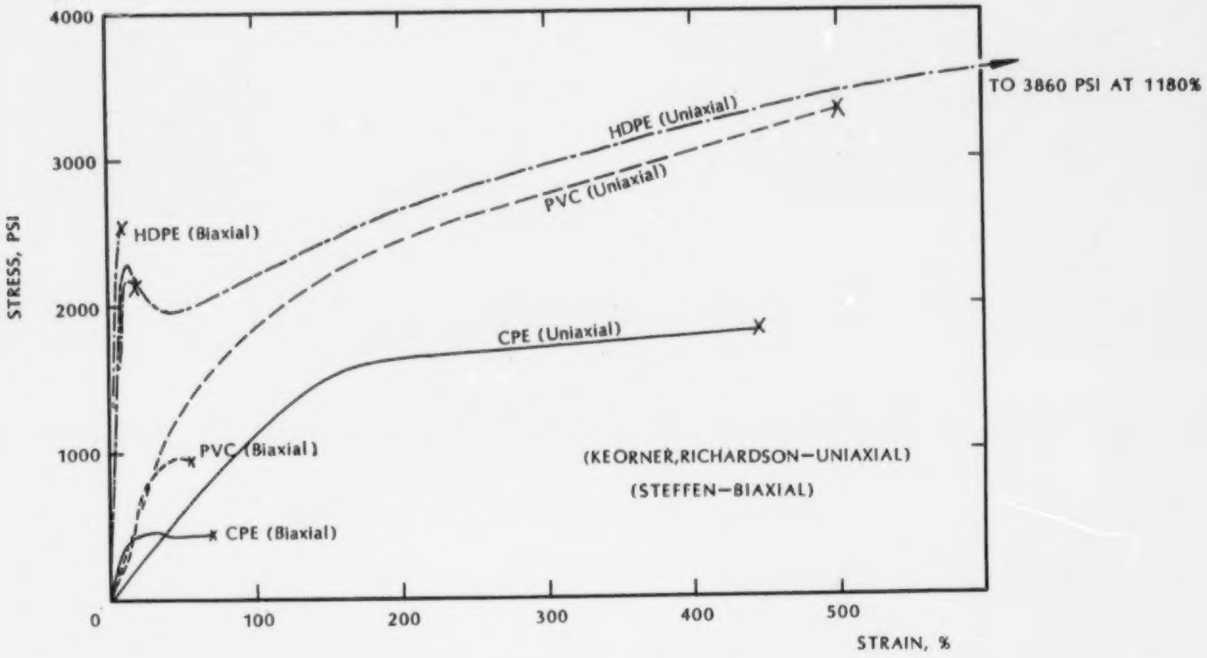


Figure 5.3 FML Stress-Strain Performance

In many facilities, it is common practice to weld the FMC to the primary FML to provide total containment of the contained waste, recall Figure 5.1b. This practice is not an MTG requirement and may lead to the transfer of stress to the primary FML if excessive settlement of the waste occurs near the edge of the cell. Such settlement would not be typical of a controlled hazardous waste cell but could occur in cells containing sanitary waste. Unless there is potential for the cell cap to be under water during peak flooding, there is nothing gained from seaming the FMC to the primary FML.

FMC Seaming

Methods used to seam polymeric membranes depend upon the composition of the membrane and the environment the membrane is placed in. For hazardous waste disposal facilities, general practice is to avoid any bonding method that will leave a residue of volitile organic solvents that may eventually be confused with leachate. This consideration aside, the common methods for seaming FMCs include adhesive or solvent bonding, thermal bonding, extrusion or fusion welding, vulcanization, and mechanical methods. Typical seam configurations currently used are shown on Figure 3.6 and details of seaming techniques are presented in Section III of this study. Some FMC seams have been developed that incorporate soil anchorage into the seam. Figure 5.6 shows a seam of a reinforced membrane that incorporates both a sewn seam and soil anchorage (Phillips, 1986).

FMC Survivability During Installation

The ability of an FMC to survive installation is dependent upon both the physical properties of the FMC and the field conditions under which it is placed. The sole design function of the FMC is to act as an impermeable layer to prevent the migration of surface water into the waste material. Of greatest concern is the accidental puncture or tearing of the FMC during installation. Construction related problems common during the installation of FMC systems include the following:

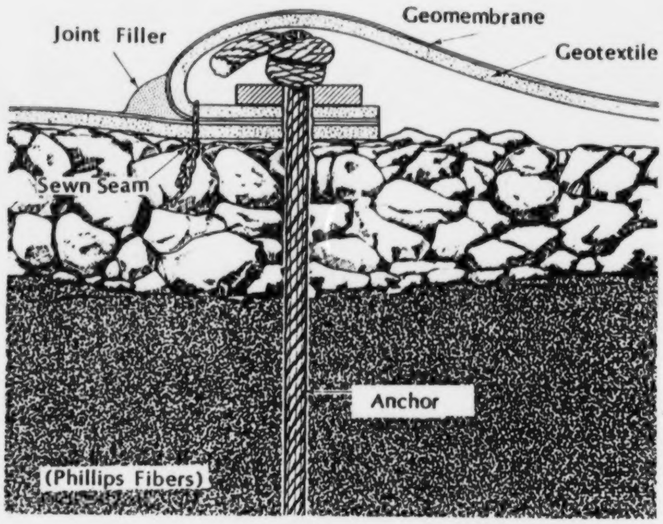


Figure 5.4 Seaming Composite Membrane

1) Subgrade preparation fails to remove large particles that can penetrate the FMC or it leaves soft zones that lead to large localized strains.

2) Placement of the surface water collection/removal system atop the FMC leads to penetration of the FMC.

3) Field handling of excessively large field panels leads to tears or excessive elongation of the FMC.

4) Installation practice leads to thermal or wind damage to the FMC.

The last installation problem relates more to fabrication practice and is discussed in Section VI. Membrane survivability during construction can be related to minimal membrane penetration and tear stress, and the use of proper bedding material above and below. Detailed criteria for FML survivability are discussed in Section III and are equally applicable to FMC survivability.

Biotic Barrier

In some locations, a biotic barrier may be advisable to reduce the potential for intrusion of animals (e.g., gophers, mice, etc.) or plant roots which can disrupt the integrity of the hydraulic barrier layer and increase percolation of surface water through burrow tunnels or root channels. Hakonson (1986) found a biotic barrier of 60 centimeters (28 inches) of 7.5 to 12-centimeter cobblestone overlain by 30 centimeters (12 inches) of gravel was effective. The cobblestones were of sufficient mass to deter burrowing animals and the large void spaces, which lacked water and nutrients, acted as a barrier to plant root developments. Research is not presently available on an optimum depth for a barrier layer; therefore, the actual thickness of the biotic barrier should be based upon site characteristics, including expected intruders, depth of plant roots, etc. Cline (1979) also reported that the use of cobbles was effective in limiting rodent penetration and also described the use of root toxins to limit the penetration of plant roots.

Past research in West Germany, Rumberg (1985), indicates that a significant danger exists to membranes from burrowing below the facility. Studies were performed with beavers and rodents to evaluate the susceptibility of various membranes to damage from burrowing. Some membranes such as soft PVC actually attracted the rodents and encouraged damage. The best performance for an unprotected membrane was in the thicker sheets of polyethylene. These rigid sheets are difficult for animals to bite. This study led to the development of test procedures that use mice (arvicola terrestris) to predict the resistance of sheet to penetration. Protective measures such as wire or glass mesh may offer a partial solution.

GAS COLLECTION and VENTING

It is rarely necessary to design for control of gases when covering a controlled hazardous waste site. Gases are evolved wherever decayable (biodegradable) organic matter is buried; thus gas control is typically a problem for sanitary but not hazardous waste landfills. Where municipal and hazardous wastes are consigned at the same site, a gas problem is likely. Where no decayable matter is buried, gas will probably not be a problem. The following discussion of gas generation is intended to provide a general review of the gas generation mechanism and not to imply that dramatic quantities of gas are to be anticipated at controlled hazardous waste facilities.

Within a few months of closure of a landfill containing organic refuse, anaerobic decay conditions stabilize, and thereafter only two gases are produced in appreciable quantity: methane (CH_4, about 55 percent by volume) and carbon dioxide (CO_2, about 45 percent by volume). Trace quantities of other gases may also be produced. The rate of waste gas production decreases steadily, but some production may persist for many years. In general, the methane gas being lighter than air is the more significant problem since it will interface with the synthetic capping system.

The most serious problem from waste gases is the explosion hazard. Methane (and some of the trace gases) is combustible, and methane-air mixtures are explosive over a certain range of composition (about 5 to 15 percent methane by volume). An explosion hazard develops when methane migrates from a landfill and becomes mixed with air in a confined space. Other actual or potential threats from waste gases include vegetation distress, odor problems, property-value deterioration, physical disruption of the cover, and toxic vapors. Vegetation kills are a demonstrated fact at landfill covers. The exact damage mechanism maybe complex, involving oxygen starvation (asphyxiation), temperature increase, plant toxicity, etc.

Of more importance to the design of controlled hazardous waste facilities, it appears that where toxic substances are buried in the absence of decaying organic matter, the threat of their vapors reaching the surface in dangerous quantities appears to be very small (EPA,1985). The chief problem is the maintenance of the integrity of the cover. The rate of migration of a vapor should be very much lower than that of a gas such as methane or carbon dioxide because of the much higher equilibrium pressure of the latter at any given temperature. Therefore, it seems logical to expect that migration of a vapor from beneath a soil cover would rarely lead to a hazardous situation. The detection and measurement of organic substances over waste sites has been a matter of recent research in California (Karimi, 1983). Vapor diffusion through cover soils at landfills is discussed in Farmer et al. (1980).

Gas-control systems make use of natural barriers when possible and of constructed barriers such as trenches, membranes, wells, and vents. Natural barriers to gas migration include moist, fine-grained soils and saturated coarse-grained soils. Lateral methane migration is controlled at a hazardous waste landfill boundary by the double FML side walls of the cell. While the the quantity of gas generated within a hazardous waste fill should be small, the presence of complete FML containment will maintain anaerobic conditions throughout the waste and maximize the methane production.

Gas withdrawn from a landfill is saturated with moisture which condenses in the collection system. During collection, the gas undergoes an expansion and temperature decline, and some water condenses. This moisture must be removed from the header to prevent freezing or saturation of the collector. The collected moisture fills the pore space of the venting system and prevents the free passage of gases. Figure 5.5 details one method of moisture drainage. The moisture is drained to a designed drainage connection that allows for continual removal of the water. For a more detailed discussion of gas control, the reader is referred to EPA (1982), or Emcon (1980).

An additional factor that needs to be considered is the possible fouling of gas drainage systems by the growth of a biomass of anaerobic slimes (EPA 1986). This problem has occurred at gas drainage wells at conventional municipal landfills. Such slimes will grow as coatings on mineral particles. The larger the pore sizes in the gas drainage layer, the longer it takes a buildup to block the pores completely. A discussion of this and other biological growth considerations is given in Section VI.

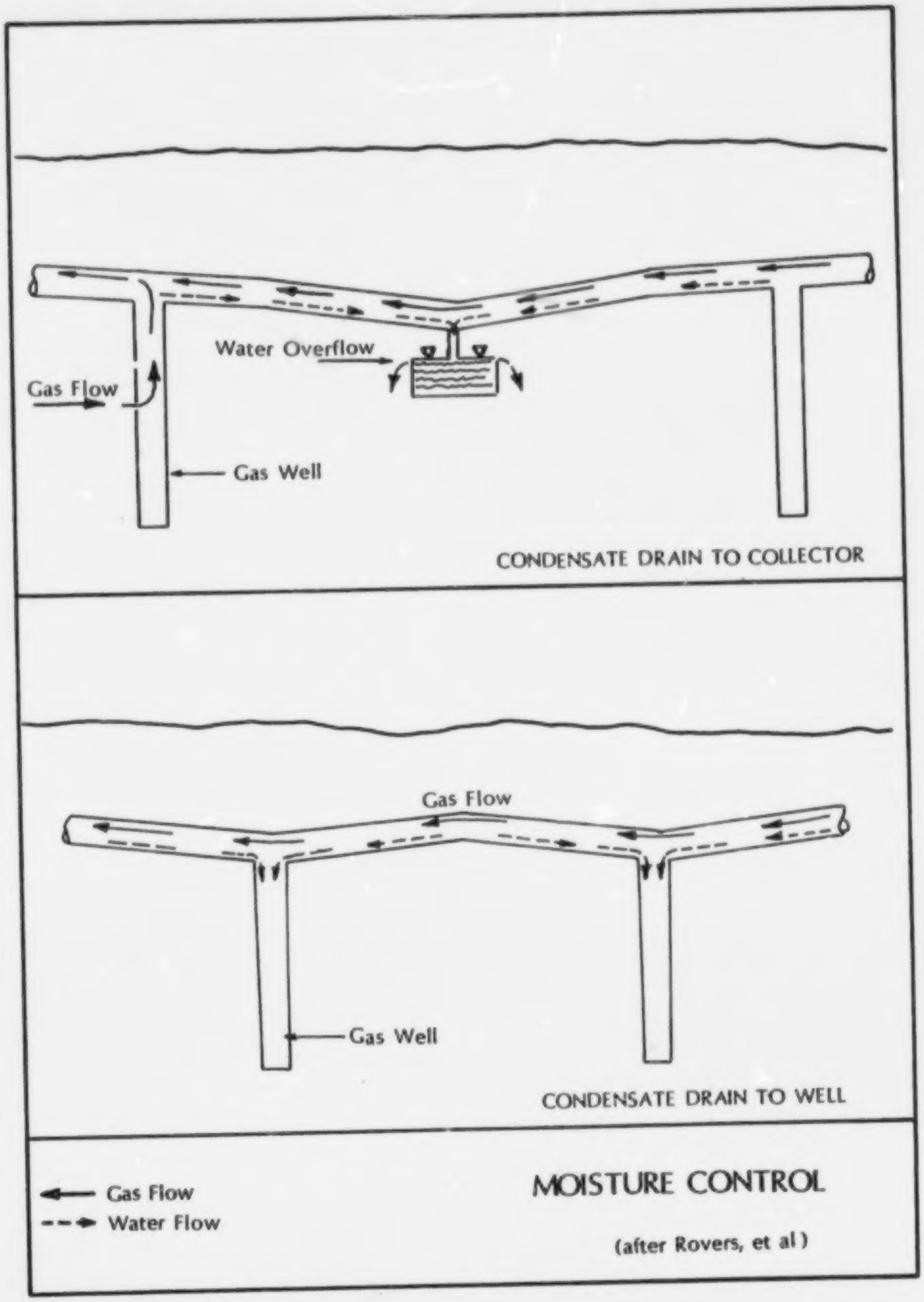

Water Overflow
Gas Flow
Gas Well
CONDENSATE DRAIN TO COLLECTOR
Gas Flow
Gas Well
CONDENSATE DRAIN TO WELL
Gas Flow
Water Flow
MOISTURE CONTROL
(after Rovers, et al)

Figure 5.5 Water Traps in Vapor Collector Systems

The gas collection system for a controlled hazardous waste facility differs from that typically designed for a sanitary facility in that the use of wells, pumps, etc. to accelerate the collection or generation of gases is not advisable due to the possible presence of hazardous vapors and the possibility of surface water intrusion through these collectors. Additionally, very little data is available to aid the designer in estimating the quantity of gas to be anticipated for a given waste inventory within the cell. Mass-balance methods to estimate gas generation rates have been proposed (EMCON, 1980); however, prior experience gained from past cells at a given site remains the best source of data. In addition to its collection function, the gas collection layer also provides a stable working bench on which the closure cap can be constructed.

Vapor Transmissivity

Gas and waste vapors rising from within the waste mass are intercepted by a gas collection layer placed between the clay component of the cap and the waste itself. This gas collector layer must allow the gases to freely flow to vent pipes that lead to the atmosphere and provide for drainage of condensate that collects. A minimum slope of 2% is required to maintain the gas flow, and slopes ranging from 2-5% are common. Kays (1977) recommends a minimum 3% slope when gas collection is a major consideration. The minimum 2% slope must be maintained even after the settlement of the waste that will naturally accompany gas generation. Current MTG guidance (EPA, 1986) recommends that the gas collection layer consist of a minimum of 30 centimeters (12-inch) of porous granular material similiar to that used in the drainage layer. Drainage layers require a minimum hydraulic conductivity of 2×10^{-2}cm/sec or a transmissivity of 3×10^{-5} m^2/s. This is the same criteria as for the synthetic LCR systems. Thus a synthetic system that satisfies design criteria for the LCR could be used as a gas collection layer.

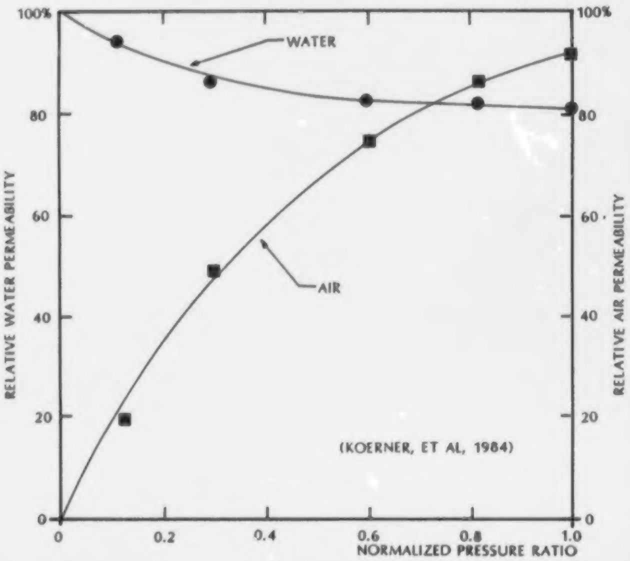


Figure 5.6 Air and Water Transmissivity in a Needled Nonwoven Geotextile

A synthetic gas venting layer can be constructed using nonwoven geotextiles or geonet/geocomposite systems. The transmissivity of the design system must be verified in the laboratory under normal loads exceeding that anticipated in the field. Both test procedures and design considerations are presented in Section III for LCRs. The only additional laboratory check that should be made is to verify that air will freely pass through the synthetic system after it has been saturated and allowed to drain. Certain nonwoven materials retain a significant volume of water even in apparent free drainage conditions due to capillary action. This retained liquid fills the void space and restricts the free movement of air or gases. Research by Koerner,et al(1983) found that the movement of air through a needled nonwoven geotextile,of 12 oz/sq.yd. was not influenced by the presence of water in the voids. Data from these tests is shown on Figure 5.6 and indicates that the presence of significant air movement can reduce the water transmissivity of the geotextile. This same study found that the air transmissivity of most nonwoven materials is several orders of magnitude greater than the water transmissivity.

Vent Pipe Details

Gases passing into the gas collection layer must be vented to the atmosphere or a collection system. The vent pipes required for this must pass through the hydraulic barrier, drainage layer, and protective cover that form the cap. Basic design variables associated with vent pipes include vent pipe diameter, vent pipe spacing, and the detail related to the vent pipe passing through the hydraulic barrier. Vent pipes are typically made of schedule 80 PVC or HDPE pipe 2 to 6 inches in diameter. A typical vent pipe design is shown on Figure 5.7 for the MTG guidance cap profile. A flexible boot must be bonded to the FMC to allow the vent pipe to pass through the FMC. The vent pipe is inserted within the boot and clamped to maintain a water-tight seal. Differential movement between the gas collection layer and the top of the cap should be minimal so that no telescopic couplings will be required for the vent pipe.

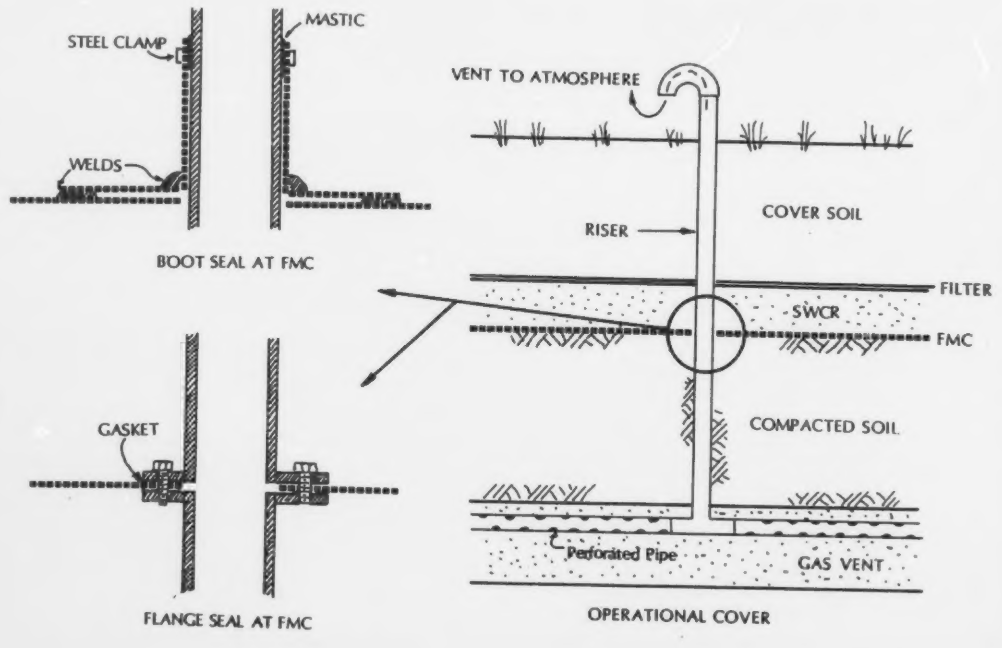


Figure 5.7 Gas Vent Pipes - Details

Vent pipe spacing is a function of the assumed rate of gas generation and the size of vent pipe used. Typical rates of gas generation assumed for sanitary landfills range from 0.5 to 7 liters per kilogram of waste per year (L/kg/yr). Lacking better data, the designer of a hazardous waste cell may assume that the level of gas generated within the cell will be a lower limit to that associated with sanitary facilities, e.g. 0.5 L/kg/yr. Designs may assume that the flow of the gas is nonturbulent such that flow is modeled by Darcy's law. This is true (Emcon, 1980) when the mean grain size of the porous media is less than 0.2 cm. This condition should be true for needled nonwoven geotextiles but may not be true for drainage nets.

References - Section V

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Cell Component: SURFACE WATER COLLECTION / REMOVAL SYSTEM

Consideration: TRANSMISSIVITY, VERIFY CAPACITY OF SWCR SYSTEM TO MAINTAIN 1-FT HEAD WITH GIVEN CAP GEOMETRY

Required Material Properties	Range	Test	Standard
PLANAR FLOW CAPACITY	10^{-1}-10^{-5} M²/SEC	TRANSMISSIVITY	ASTM D4617

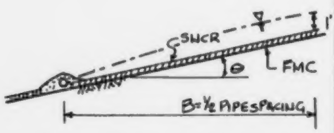
Draft MTG Minimum

Analysis Procedure:

(1) DEFINE MINIMUM TRANSMISSIVITY

- 1-FOOT HEAD

$$T = \frac{B^2 * q}{h_{MAX} + B \sin \theta}$$



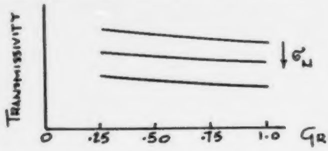
q = LEACHATE INFLOW RATE
h_{MAX} = 1 FOOT OF HEAD

(2) CALCULATE MAXIMUM NORMAL STRESS

$$\sigma_N = D * \gamma$$

D = FINAL DEPTH CAP TO LCR
γ = UNIT WEIGHT OF FILL

(3) OBTAIN LABORATORY TRANSMISSIVITY DATA



GRADIENT, $\Delta h / L = \frac{h_{MAX} + B \sin \theta}{(B / \cos \theta)}$

(4) DEFINE DESIGN RATIO

$$DR = \frac{T_{LCR}}{T_{REQUIRED}}$$

Design Ratio:

$DR_{MIN} = 10.0$

References:

WONG (1977)

Example:

GIVEN:

- COVER SOIL HEIGHT, D = 4'
- UNIT WEIGHT OF COVER SOIL, γ = 120 PCF
- SLOPE ANGLE, θ = 8°
- SPACING OF COLLECTOR PIPES = 120 FT
- LABORATORY TRANSMISSIVITY DATA
- SURFACE WATER INFILTRATION RATE, q = .1 FT³/FT²/DAY

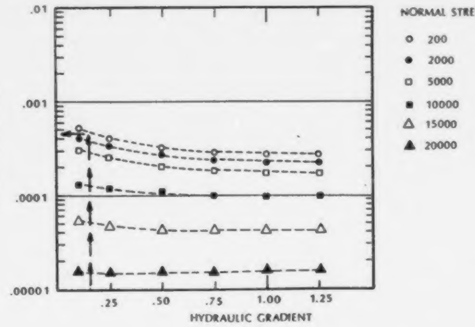
(1) DEFINE MINIMUM TRANSMISSIVITY

$$T = \frac{60^2 * 0.1}{1 + 60 \sin 8^\circ} = 38.5 \text{ FT}^2/\text{DAY} = \underline{\underline{4.1 \times 10^{-5} \text{ M}^2/\text{SEC}}}$$

(2) CALCULATE MAXIMUM NORMAL STRESS, σ_N

$$\sigma_N = 120 \times 4 = 480 \text{ PSF}$$

(3) OBTAIN SWCR TRANSMISSIVITY FROM LAB DATA, T_{SWCR}



GRADIENT, $i = \frac{1 + 60 \sin 8^\circ}{(60 / \cos 8^\circ)}$

$\underline{\underline{i = .154}}$

$T_{SWCR} = \underline{\underline{.00045 \text{ M}^2/\text{S}}}$

(4) CALCULATE DESIGN RATIO

$$DR = \frac{T_{SWCR}}{T_{REQ.}} = \frac{.00045}{4.1 \times 10^{-5}} = \underline{110} \qquad \text{O.K.}$$

Example No. 5.1

Cell Component: SURFACE WATER COLLECTION/REMOVAL SYSTEM

Consideration: SHEAR FAILURE: EVALUATE SLIDING STABILITY OF COVER SOIL AND DESIGN RATIO AGAINST SHEAR FAILURE OF SWCR.

Required Material Properties	Range	Test	Standard
FRICTION ANGLES			
· COVER SOIL TO SWCR, δ_U	30°-45°	DIRECT SHEAR	ASTM PROPOSED
· SWCR TO FMC, δ_L	10°-40°		
SHEAR STRENGTH OF SWCR, τ_{ALLOW}	10-100 lb/in²	WIDE WIDTH	ASTM D4595

Draft MTG Minimum

Analysis Procedure:

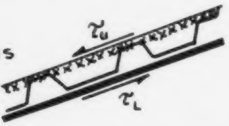
(1) CALCULATE DESIGN RATIO FOR COVER

$$DR = \frac{\tan \delta_U}{\tan \beta} \qquad \beta = \text{SLOPE OF COVER}$$

(2) CALCULATE SHEAR STRESS ABOVE & BELOW SWCR SYSTEM

$$\left.\begin{array}{l} \tau_U = \sigma_N \tan \delta_U \cos\beta \\ \tau_L = \sigma_N \tan \delta_L \cos\beta \end{array}\right\} \text{LOWER GOVERNS}$$

$\sigma_N = D * \gamma$ D = THICKNESS OF COVER SOIL



(3) CALCULATE DESIGN RATIO FOR SWCR SHEAR

$$DR = \frac{\tau_{ALLOW}}{\sigma_N \tan \delta_{MIN}}$$

Design Ratio:

COVER SLIDING	DR > 2.0
SWCR SHEAR	DR > 5.0

References:

MARTIN, ETAL (1984)

KOERNER, ET AL (1986)

Example:

GIVEN:
- FRICTION ANGLES
  - COVER SOIL TO SWCR = 40°
  - SWCR TO FMC = 25°
- SLOPE ANGLE = 5.7°
- COVER SOIL DEPTH = 4'
- COVER SOIL DENSITY = 120 lb/ft³
- SHEAR STRENGTH SWCR = 15 lb/in²

(1) CALCULATE DESIGN RATIO FOR COVER

$$DR = \frac{\tan 40°}{\tan 5.7°} = 8.0 > 2.0 \quad \underline{OK}$$

(2) CALCULATE SHEAR STRESS ABOVE & BELOW SWCR

$\sigma_N = 4 \times 120 = 480$ PCF

$\tau_U = 480 \tan 40° \cos 5.7° = 401$ PCF

$\tau_L = 480 \tan 25° \cos 5.7° = 223$ PCF ← GOVERNS

(3) CALCULATE DESIGN RATIO FOR SWCR SHEAR

$$DR = \frac{15 \times 144}{223} = 9.6 > 5.0 \quad \underline{OK}$$

Example No. 5.2

Cell Component: SURFACE WATER COLLECTION/REMOVAL SYSTEM

Consideration: TENSILE STRESS: EVALUATE ABILITY OF SWCR TO RESIST TENSILE FORCES RESULTING FROM IMBALANCE IN SHEAR CAPACITIES.

Required Material Properties	Range	Test	Standard
FRICTION ANGLES			
• COVER SOIL TO SWCR, δ_U	30°-45°	DIRECT SHEAR	ASTM PROPOSED
• SWCR TO FMC, δ_L	10°-40°		
TENSILE STRENGTH OF SWCR, T_{ULT}	500-3000 lb/IN	WIDE WIDTH	ASTM D4595

Draft MTG Minimum

Analysis Procedure:

(1) CALCULATE SHEAR STRESS ABOVE & BELOW SWCR

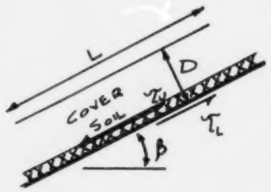
$\tau_U = \sigma_N \tan \delta_U \cos\beta$ $\tau_L = \sigma_N \tan \delta_L \cos\beta$

$\sigma_N = D \times \gamma$

D = THICKNESS OF COVER SOIL
β = SLOPE

(2) CALCULATE TENSION IN SWCR

$T_{MAX} = (\tau_U - \tau_L)\, L$



(3) CALCULATE DESIGN RATIO

$$DR = \frac{T_{ULT}}{T_{MAX}}$$

T_{ULT} = ULTIMATE TENSILE STRENGTH OF SWCR

Design Ratio:

DR > 5.0

References:

Example:

GIVEN:

- FRICTION ANGLES
  - COVER SOIL TO SWCR = 40°
  - SWCR TO FMC = 25°
- SLOPE ANGLE 5.7°
- COVER SOIL DEPTH = 4'-0"
- TENSILE STRENGTH OF SWCR = 460 lb/IN
- SLOPE LENGTH = 200 FT.

(1) CALCULATE SHEAR STRESS ABOVE & BELOW SWCR

$\sigma_N = 4 \times 120 = 480$ PCF

$\tau_U = 480 \tan 40° \cos 5.7° = 401$ PSF
$\tau_L = 480 \tan 25° \cos 5.7° = 223$ PSF

(2) CALCULATE TENSION IN SWCR

$T_{MAX} = (401-223)\,200 = 35600$ lb/FT $= 2970$ lb/INCH

(3) CALCULATE DESIGN RATIO

$DR = \frac{460}{2970} = \underline{\underline{0.15}}$

NG

Example No. 5.3

Cell Component: Flexible Membrane Cap

Consideration: Settlement : Verify ability of FMC to survive settlement resulting from long-term waste compression. Settlement features may be biaxial or uniaxial.

Required Material Properties	Range	Test	Standard
Flexible Membrane Cap - Yield strain for FML, ϵ_{YIELD}	10-25%	Widewidth	ASTM D4595

Draft MTG Minimum

Analysis Procedure:

(1) Estimate Geometry of Settlement Depression

- Depth based on % settlement × waste depth (suggest minimum 5%)
- Width based on minimum cell dimension or past experience

(2) Calculate Settlement Ratio, SR

SR = depth / width

(3) Obtain Uniform Strain from Fig 3A

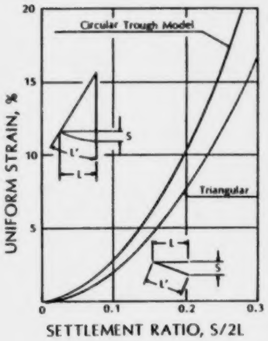
suggest circular trough model

(4) Obtain Stress/Strain for FMC

→ ϵ_{RUPT} (strain at rupture)

(5) Calculate Design Ratio

DR = $\epsilon_{RUPT} / \epsilon_{UNIF}$



Design Ratio:

DR$_{MIN}$ > 5.0 Rupture

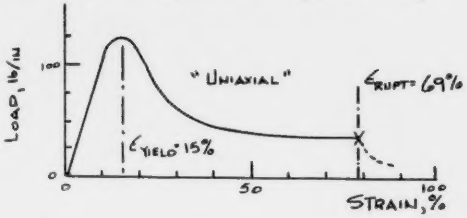
References:

Knipschield (1985)

Example:

Given:

- Minimum width of cell = 50 ft
- Depth of waste = 50 ft
- Composite FMC [Geotextile + Geomembrane]



(1) Estimate Geometry of Settlement Feature

- Settlement depth = 5% × 50' = 2.5 ft

(2) Calculate Settlement Ratio, SR

- SR = 2.5/50 = .05

(3) Obtain Uniform Strain, ϵ_{UNIF}

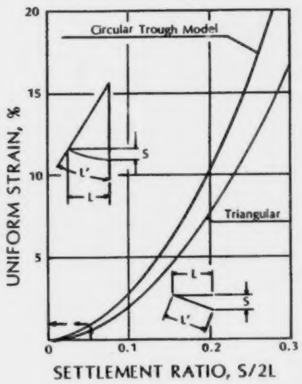
See Figure → ϵ_{UNIF} = 1%

(4) Stress/Strain for FMC

→ ϵ_{RUPT} = 69%

(5) Calculate Design Ratio

DR = 69/1 = 69 OK



Example No. 5.4

SECTION VI

CONSTRUCTION/FABRICATION CONSIDERATIONS

The successful application of geosynthetics to hazardous waste landfills and surface impoundments requires the interaction of the design engineer, manufacturer, installer, contractor, and owner/operator. These may be separate companies or may be under a single company. The individual responsiblities are as follows:

1) engineer - design of components

2) engineer - prepare specifications

3) manufacturer/installer - fabrication of component

4) installer/contractor - installation of component

5) manufacturer/installer - quality control of component

6) owner/operator/third party engineer - quality assurance for component

The interaction of these groups will depend upon the particular component and the management structure of the particular facility. Some components, such as FMLs, may be installed by the company that actually manufactures and fabricates the membrane. Other components, such as geotextiles, are commonly installed by the general contractor for the overall facility construction.

Minimum requirements for construction quality assurance for hazardous waste land disposal units have been established by EPA in a recent Technical Guidance Document,TGD (EPA, 1986a). Under this program, construction quality control (CQC) activities are defined as those performed by the construction contractor, manufacturer, or fabricator to control the quality of the constructed or installed component. These activities include a planned system of inspections used to directly monitor and control the quality of the construction. Construction quality assurance (CQA) is defined as a planned system of activities that provide assurance that the facility is constructed as specified in the design. Development and implementation of a CQA program is the responsibility of the facility owner/operator. Well planned and implemented quality CQC/CQA programs begin during design and proceed through installation and operation of a landfill or surface impoundment. Frequently these services are provided by a third party engineer.

The type and implementation of CQC/CQA programs have varied greatly within the industry. Prior to the TGD there was no industry-wide standard practice. Recommendations from several designers and manufacturers regarding CQC/CQA suggest that the following items be incorporated into CQC/CQA programs:

- A checklist to assure all facility requirements have been met.

- A specific plan to be used during construction for observation, inspection and testing of subgrade, liner material, factory and field seam quality, installation workmanship, and assurance that the design is followed. Daily records must be maintained of all aspects of the work, including tests performed on the subgrade and liner, as for example, vacuum box seam testing with periodic field seam tensile testing.

- Throughout construction, a qualified auditor responsible to the operator/owner should review and monitor output. This is an ongoing check on the contractor/installer. It generates confidence that the work was indeed done as planned. Changes to planned procedures must be justified immediately and subsequently documented.

CQC/CQA programs can result in more effective installations by assuring planned review and tracking of all installation activities.

FLEXIBLE MEMBRANE LINERS/CAPS

The installation of flexible membrane liners requires proper planning before construction. This planning includes development by the engineer of contract specifications for the components, development of fabrication details by the manufacturer/installer, and performance of CQC/CQA procedures by the owner/operator and installer to verify material quality and field procedures. Many of the important elements of installation must be reviewed and inspected by the component installer, the general contractor, and the owner/ operator. These important elements of installation include subgrade preparation, onsite storage of materials, installation equipment, manpower requirements, procedures for liner placement, field seaming procedures, sealing around structures or penetrations, quality control/quality assurance procedures and soil cover requirements. For many facilities, the design engineer serves as an agent of the owner/operator for these Quality Assurance functions. Conversely, it is not unusual for the owner/operator to use in-house engineering to perform all of the engineering functions for the facility.

Specifications

A synthetic liner is covered by overlapping layers of specifications that include those prepared by the membrane manufacturer, the installer, and by the design engineer. Those specifications prepared by the engineer are project specific and include performance specifications that reflect the actual design. These specifications are the minimum standards for the project but may be superseded in part by more rigid specifications of the manufacturer or installer. With the exception of performance specifications, the specification concerns presented here are commonly found in manufacturer's, installer's and the design engineer's specifications. The design engineer should indicate that the project specifications can be superseded by more stringent specifications of the manufacturer or installer. The project specifications prepared by the engineer are, however, the minimum specifications for the FML.

While no two projects have identical specifications, those prepared by the manufacturer, installer, and the engineer will typically cover the following concerns: 1) Document Control, 2) Raw Material, 3) Manufactured Sheet, 4) Delivery and Storage, 5) Installation, and 6) Sampling and Testing. Since most liner projects are bid to the installers, it is important that any discrepancies in the specifications of the involved parties be resolved very soon after the FML contract is awarded. The document control program is part of the CQC/CQA program discussed later in this section. Very soon after award of the FML contract, a document control program that satisfies the needs of the facility CQA officer must be established.

Raw Material---

Synthetic polymer resins are manufactured by many large chemical companies and generally delivered to liner manufacturers in bulk rail cars. These resins resemble granular or powdered sugar and must be tested to ensure their quality before being fabricated into manufactured sheet. The FML manufacturers will typically include the following tests of the resin in their product specifications:

1) Density (ASTM D-1505), expressed as the weight per unit volume at 23 degrees C.

2) Melt Index (ASTM D-1238), qualifying the molecular weight of the material as demonstrated by the rate at which it flows through a .0825-inch diameter orifice.

3) Percent Moisture (ASTM D-570), expressed as a percent moisture.

These tests are the initial 'finger print' tests used to qualify resin prior to its being formed into sheet. Typical limits for HDPE materials are given in the Appendix on geosynthetic properties. An additional test used by a limited number of sheet manufacturers is infared spectroscopy. This test produces a curve that can be overlayed to a standard curve for acceptance. It is important that the FML material delivered to the field be the same as used in the chemical compatibility testing, e.g. EPA9090. Sheet manufacturers will typically retain a bag sample of each lot of raw resin used. These samples are retained for use in litigation should major failure of a given lot of manufactured sheet occur. The key finger printing tests then become thermo-gravametric analysis (TGA) and differential scanning calorimeter (DSC), reference Haxo, 1983.

Manufactured Sheet--

The resin is processed into manufactured sheet using an extrusion, calendering or spread coating processes. Samples of the manufactured sheet are taken during production and after a conditioning period. The frequency of sampling may be based on a minimum number of samples per shift (or 24 hours), or resin batch, or roll. Unfortunately, there is no standard requiring production sampling on the basis of square footage produced. Thus the sampling rate can vary between manufacturers. The finished sheet samples are then subjected to the minimum following tests:

1) Thickness (ASTM D-1593)

2) Tensile Properties (ASTM D-638), defining the tensile

strength at yield and break, and the elongation at yield and break.

3) Tear Resistance (ASTM D-1004), expressed in pounds.

4) Carbon Black Content (ASTM D-1603), expressed as a percent.

5) Carbon Black Dispersion (ASTM D-3015)

6) Dimensional Stability (ASTM D-1204)

7) Stress Crack Resistance (ASTM D-1693)

These tests provide a signature of the finished product and are not design oriented. Specifications must ensure that the specific polymer material tested for both physical and chemical properties is the same as delivered to the job site. It is suggested that density and molecular weight measurements be taken on a periodic basis. Additionally, any significant variation in the values obtained from these tests indicates a production quality control problem. Published values for these properties are given in the appendices for many available geomembranes. A brief description of each test procedure is also presented in the appendices.

Delivery and Storage--

FML material is typically shipped to the job site in rolls or folded on pallets depending on the polymer used to form the FML. For instance, polyethylene should never be folded under any conditions and will always be delivered to the site in rolls. Project specifications must require that each roll or pallet be stored off the ground and protected with a covering that prevents physical damage, contamination by dust or water, and exposure to direct sunlight. The specifications should also require that each roll or pallet be identified with the following minimum information (Schmidt, 1983, EPA 1986b):

1) Name of manufacturer/fabricator,
2) product type,
3) product thickness,
4) manufacturing batch code,
5) date of manufacture,
6) physical dimensions (length and width),
7) panel number per design layout pattern, and
8) direction for unrolling panel.

The site CQA officer should inspect each roll or pallet of FML to ensure compliance with these specifications and maintain a record of all roll identification tags.

Project specifications should require that all geomembranes delivered to the job site be stored in a secure area that protects the panels from vandalism by man or animal, contamination by dirt, dust or water, and from extreme heat caused by direct sunlight. Typical specifications will limit the extreme temperature of the membrane to less than 140° F to prevent blocking (sticking) of the rolled or folded panel faces together. If the climate is hot, then the geomembrane should be conditioned(e.g. by powdering) to prevent blocking. The geomembrane should be stored in a air conditioned room, if necessary, to prevent loss of plasticizers (PVC) or curing (CSPE). Manufacturers quality control programs are typically somewhat vague and simply require storage that 'prevents damage to any part of the product'. Many such QC manuals do, however, limit the stacking height of rolls (usually to two) and should be inclusive in the designers specifications.

Installation--

Installation specifications for geomembranes are focused on a visual inspection of the manufactured sheet and the quality of field seams. Field weld specifications will require daily quality control testing of the welding procedure and inplace seams. Daily CQC testing of the welding procedure should require that a field test weld section be tested several times during a given shift. The length of the test weld will vary depending upon the weld type. Typically test lengths for HDPE are 3 feet for extrusion welds and approximately 1 foot for hot shoe (wedge) welds. Manufacturers specifications will require testing ranging from manually pulled 'peel' test that base acceptance on seam failure occurring in the parent material, to the tests required under NSF 54 Standards. These tests require 1 inch samples to be tested in both peel and shear. The designer should review the field QC specifications of prospective manufacturers/installers and require minimum NSF 54 testing in the general project specifications. Details of in-place seam testing are discussed below.

Sampling and Testing--

It is generally recognized that the geomembrane industry can produce a flawless sheet but experiences difficulty in maintaining this level of quality in seaming two sheets together. Flawless field seams are difficult to obtain for the following reasons (Koerner,1987):

- sloped preparation surface
- nonuniform (or yielding) preparation surface
- nonconforming sheets to the subsurface (air pockets)
- slippery liners made of low friction material
- wind-blown dirt in the areas to be seamed
- moisture and dampness in the areas to be seamed
- penetrations, connections and appurtenances
- wind fluttering the sheets out of position
- ambient temperature variations during seaming
- uncomfortably high (and sometimes low) temperature for careful working
- expansion and/or contraction of sheets during seaming

The sampling and testing program must be designed to detect such problems and to adjust the frequency of testing when required by field conditions.

Project specifications must require that FML seams be 100% tested using a nondestructive technique such as vacuum box or ultrasonics. Lord (1986) summarized NDT tests for typical polymers, Table 6.1. The ultrasonic shadow method has only recently been added to this list of NDT tests. Koerner(1987) presents a summary of this latest NDT test on HDPE seams. The specific test procedures for such testing should be detailed in the project specifications since applicable standards are not available at

Table 6.1 Available NDT Methods for Evaluating Seams

Geomembrane system	Air lance[a]	Vacuum chamber[b]	Pressurized dual seam	Electrical sparking[c]	Mechanical point stress	Electronic Ultrasonic pulse echo (5-15 MHz)	Electronic Ultrasonic shadow (0.5-5 MHz)	Electronic Ultrasonic impedance (160-185 kHz)
Thermoplastics (PVC, TN-PVC; EIA)								
Reinforced	X	X			X		X	
Nonreinforced	X	X			X	X	X	X
Crystalline thermoplastics (LDPE; HDPE)								
Nonreinforced		X	X	X	X	X	X	X
Elastomers (Butyl; EPDM; CR; CO)								
Reinforced	X	X			X		X	
Nonreinforced	X	X			X		X	
Thermoplastic elastomers (CPE; Hypalon; T-EPDM)								
Reinforced	X	X			X		X	X
Nonreinforced	X	X			X	X	X	X

[a] Air lance should be restricted to thickness less than 45 mils; this method is not recommended for stiff sheeting.
[b] Vacuum chamber should be restricted to 30 mils and greater due to deformation.
[c] Electronic methods do not work on EIA material.

present. For the vacuum test, the level of vacuum and dwell time at a given location can influence the test results. Unfortunately, in most installations this CQA testing is performed by the same group installing the FML. Thus it is important that the general project specifications clearly detail the procedure that must be used in performing this test. Seam sections that fail must be repaired 'in accordance with approved techniques' and retested. The 'approved' technique, is typically simply to grind down the old extrusion weld and reweld, or, in the case of hot shoe welds, to put an additional cap strip of FML material over the seam and reweld.

Destructive samples of field welds must be taken at locations and frequencies given by the project specifications. Typical installer CQC programs do not require destructive field tests, so the general project specifications must clearly define this testing if it is to take place. The frequency and location of samples are the most difficult considerations to define. Excessive sampling can lead to weakening of the seam and a proliferation of failure prone patches. The discussion of Construction Quality Control/Quality Assurance for FMLs in this section gives guidance for established sampling strategies. The FML samples removed at a given location should be large enough for the installer to check, for an independent laboratory to check, and for owner/operator archiving. The project specifications should clearly specify the protocol and role of all parties in the testing and acceptance of destructive samples.

Fabrication

The manufactured sheet used to form a FML may go through several fabrication processes that the design engineer should review. Many FML sheets are produced in widths of 4 to 6 feet that are fabricated into wider sheet by the manufacturer prior to shipment to the installer. For other sheeting, e.g. HDPE, the manufactured sheets are sufficiently wide that all of the fabrication is performed by the installer. The design enginner should review the methods and orientation of all factory or field seams to ensure that design physical properties are not compromised.

The general panel layout for a given facility is normally provided by the installer. The design engineer should review the panel layout to check that the following guidelines are met:

1) Field seams should run up-and-down the slope and not terminate at the bottom of the slope but runout for a minimum distance of 3 feet.

2) Overall field seam length should be minimized.

3) No penetration of the primary FML below the top-of-waste elevation should occur.

The installer should submit the general panel layout for approval by the design engineer and for use by the project CQA engineer in monitoring the FML sheeting as it arrives on the job site. At this time, the two parties should agree upon a numbering scheme for both the panels and the welds between the panels. A typical numbering scheme is shown in Figure 6.1. This numbering scheme plays an important role in assuring that prefabricated panels are properly positioned during installation and that CQA records of seam tests are clear regarding the location of seaming difficulties.

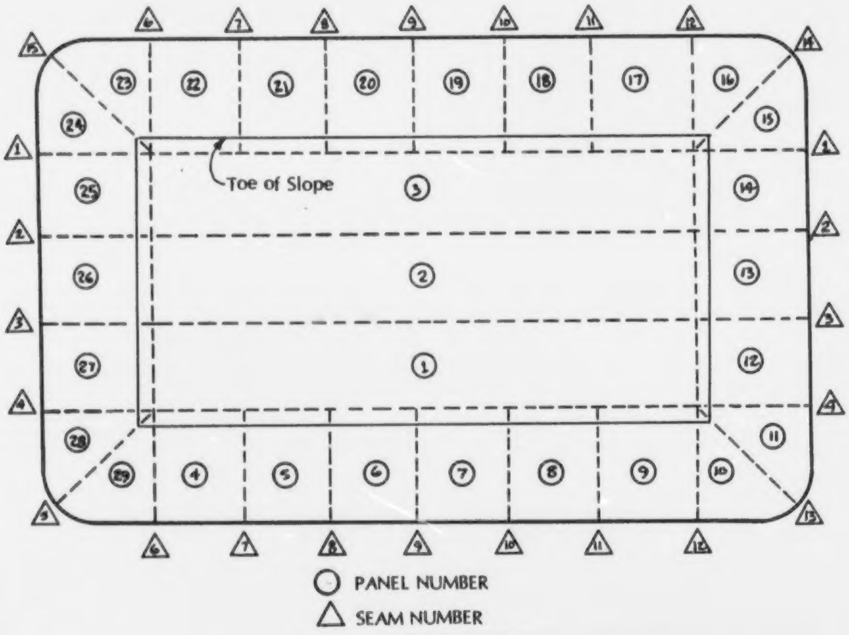


Figure 6.1 Panel-Seam Identification Scheme

Construction

Successful installations of an FML system were found by Schultz (1983,1985) and Bass (1984) to depend on the experience of the field installation crew and their attention to significant construction details. This Section reviews the field details that influence the quality of installation. While the topics are similiar to that discussed in Section II, the emphasis in this section is on construction procedures and not on design of the FML which is covered in Section III.

On-site Storage of Material--

Membrane materials are normally shipped to a construction site, and must be stored prior to placement. Most materials are rolled on tubes or folded and shipped on wooden pallets. Provisions should be made for equipment to unload and transfer the rolls or panels of synthetics. The rolls are generally very heavy and may require special or modified equipment to move them without damaging the material. Protection for the liner materials from the effect of heat and from vandalism by man or damage by animals is required. These are the most important storage considerations. All FML's, except HDPE, should be stored out of sunlight to prevent their degradation and minimize blocking. Blocking occurs when liner materials stick together, causing the material to rip when it is unrolled onto the subgrade. Excessive heating can also degrade the surface of the material, causing problems with field bonding. Covering the material with white plastic or storage out of direct sunlight is recommended for all materials.

Installation Equipment--

Equipment often required to install a membrane liner includes a fork lift truck, backhoe, or front end loader for material placement and various tools necessary for material positioning and field seaming. A fork lift truck, with large rubber tires (not warehouse type), is most often recommended for material placement, because some material is shipped to a site on wooden pallets. All equipment should be limited to 6 psi or less ground contact pressure.

The equipment needed to seam the material together is basically similar for all types of material, with the exception of high density polyethylene. High density polyethylene is fused or welded together and requires special equipment.

Manpower Requirement--

Manpower requirements for the installation of liner materials is a function of the rate that the installer wants to place panels and accomplish field seaming. Typically, installation contractors will recommend five to ten people on site when placing and seaming one panel at a time. Generally, a crew foreman will direct the activities of the field crew. He may not directly participate in the unrolling and positioning of panels or in field seaming. However, he must be experienced in the installation of the specific liner material.

Crew size recommendations also depend on the complexity of the installation and the experience of the field crew. If the majority of the crew members are recruited locally, more members may be needed due to lack of experience. At the present time, the trend is toward having installation contractors retain field supervisors who travel from job site to job site. Large jobs where crews perform specific tasks may involve many locally recruited and inexperienced people.

Project specifications prepared by the designer commonly stipulate minimum experience levels for the installers foreman and field supervisors. While difficult to implement, such specifications do ensure a minimun experience level for the installer. Such specifications typically require a minimum of one year experience for the foreman and no less than 3 months experience for the field supervisors. Alternately, specifications may require experienced based of square footage of installed FML. Such experience must be continous and with the same polymer membrane selected for the project.

Liner Placement--

Important considerations that should be followed in placing a membrane liner are as follows (Schultz,1985):

- Follow manufacturers' recommended procedures for adhesive system, seam overlap, and sealing to concrete
- Use a qualified installation contractor having experience with membrane liner installation, preferably the generic type of liner being installed
- Plan and implement a quality control program which will help ensure that the liner meets specification and the job is installed per specifications
- Document inspection for review and recordkeeping
- Conduct installation during dry, moderately warm weather (above 45^{o}-60^{o}F depending on material)
- Subgrade should be firm, flat, and free of sharp stones, gravel or debris.

Before moving a panel from the storage site to the installation location, a number of tasks must be performed. The anchor trench around the perimeter of the installation for the panel should be completed. The soil excavated from the anchor trench should be raked smooth on the cell side of the trench so that the panels can be unrolled . Other things that must be accomplished prior to positioning a panel are: (1) the subgrade should be raked smooth or compacted if necessary; (2) there should be no standing water in the cell or impoundment; (3) any concrete structures that must be seamed around should be prepared prior to unrolling the panel; (4) if skirts are to be used around footings on concrete structures, these may be in place prior to the beginning of panel placement; and (5) any outflow or inflow structures or other appurtenances should be in place.

Placement often begins with the unfolding or rolling of the panel in a lengthwise direction. If necessary, the panel is then unfolded in the width direction, either down the side slope or across the floor. The panels are normally unrolled on the inside of the anchor trench, eliminating the need to move the liner across the trench. The field crew then begins to position or "spot" the panel into its proper location according to the installation plan. As panels are spotted, sand bags are placed along the edges to prevent uplift and subsequent wind damage. Sand bags are typically required at a minimum spacing of 2-foot centers on the windward edge of the panel. If the windward side cannot be identified, then the sandbags must be placed around the entire panel. These sandbags may be left in place until the completed liner is stabilized by placement of overlying components. A method for calculating the number of sandbags required at a give site is discussed later in this section. Note that old rubber tires are not recommended in place of sandbags because they lack enough weight to be effective and hold water that can spill onto work areas. Wind induced lifting of the membrane is strongest near the top of the berms and nearest the corners. In surface impoundments, the wind lift problem may continue to exist during operation of the SI. In these cases, vents similiar to gas vents are installed to allow the wind to suck the air out from under the liner. A vent similiar to that used for gas venting, see Section V, is used for such applications.

The instructions on the boxes containing the liner must be followed to ensure that the panels are unrolled in the proper direction with the correct side exposed for seaming. The panels should be pulled relatively smooth over the subgrade. If the subgrade is smooth and compacted,then the liner should be relatively flat on the subgrade. However, sufficient slack must be left in the material to accommodate any possible shrinkage due to temperature changes. The amount of slack required depends on the material being installed.

The FML panels should be spotted in such a way that sufficient seam overlap of the adjacent panel is maintained. Recommended overlap varies from 3 to 6 inches. The installation contractor should, however, follow the manufacturer's recommendations in terms of overlap and bonding system. The integrity of field seams depends on the following factors:

1. Manufacturer's guidelines for adhesives should be followed. The seaming system must be compatible with the FML and be applied under the correct ambient condition;

2. Cold temperatures can prevent successful bonding of panels. Some manufacturers recommend that adhesive bonding take place only when temperatures are above $60^{o}F$ ($15^{o}C$);

3. The seam surface must be clean and dry. The presence of moisture interferes with the curing and bonding characteristics of the adhesive, while the presence of dust creates voids which provide a path for fluid migration through the seam. Either soil particles or moisture embedded in the seam can result in crack initiation points which expand with stress and aging.

4. The liner should rest on a dry, hard and flat surface to facilitate the application of pressure rollers; and

5. Panels should be installed and seamed on the same day to minimize the risk of FML damage by wind and erosion of soil under the FML by rain.

The finished seams should be free of wrinkles and the surface should be flat and rolled. Some manufacturers recommend that field seaming begin at the center of the panel and continue to each end of the seam. This procedure minimizes large wrinkles or 'fishmouths' which may potentially occur if seaming begins at the ends.

As in compaction of a soil liner, placement of the FML on the facility sideslope is a critical aspect of liner construction. Generally the panels should be of sufficient length to be placed so that field seams will run perpendicular to the toe of the slope (i.e., seams should run vertically rather than horizontally along side slopes). This method reduces stress on field seams. Corner patterns should be cut for fit in a tailored fashion.

Field Seaming--

The panels should be unfolded and spotted so that a sufficient seam overlap of the adjacent panel is maintained. Some materials, such as HDPE, must be allowed time to relax and temperature adjust prior to seaming. Seam overlap recommendations vary with liner manufacturer and liner type. Recommended overlaps vary from 3 to 6 inches.

Field seaming is a critical factor in flexible membrane liner placement and is discussed in greater detail in Section III. Liner manufacturers publish recommended procedures for achieving successful field seams with one of four methods generally recommended to seam materials in the field. These are as follows;

o Solvents: bodied adhesive, solvent adhesive, or contact adhesive,
o Thermal : hot wedge, hot air, and dielectric,
o Introduction of hot base: extrusion or fusion, and
o Vulcanization with uncured gum tape or adhesive.

The installation contractor should use the manufacturer's recommended procedure. In some instances, an installer may have worked with a manufacturer to develop an improved technique for that installer. In such a case, the method should be allowed if it meets peel/shear testing requirements and chemical compatibility restrictions.

The integrity of the field seam is determined by many factors. The most important factor is that the seaming system used must be compatible with the liner material and suitable for use under actual field conditions. Generally, manufacturers recommend seaming at temperatures above 45°-60°F depending on the material. If ambient temperatures are below this range, some manufacturers suggest installation activity cease. Many HDPE manufacturers allow seaming at temperatures significantly below this level. Such cold weather seaming requires more destructive seam tests to ensure bonding for seam integrity. Another important factor in field seam integrity is that the surfaces to be seamed are clean and dry when the field seams are made. The presence of any moisture can interfere with the curing and bonding characteristics of the adhesive used. The presence of any dirt or foreign material can jeopardize seam strength and provide a path for fluid to migrate through the seam or as stress crack initiators.

An upper temperature limit for thermal and extrusion weld field seaming is commonly related to the installer and not the installation procedure. With welds occurring at 500°F (260 °C), the human installer becomes the limiting factor with increased temperature. High ambient temperatures may quickly evaporate the active agent in solvent cements and require a significant reduction in length of seam prepared at a given time. The consistency of the solvent cement should be checked frequently to verify that excessive amounts of the solvent have not evaporated.

With the exception of extrusion welding, pressure must be applied to a seam after the solvent, adhesive, or heat has been applied. Therefore it is recommended that the liner ideally should rest on a dry, hard flat surface for rolling. Installers recommend that a board or other suitable hard surface be placed underneath the overlap of the liner material. Overlaps can be anywhere from 3 to 6 inches wide, depending on the type of material and the conditions under which seaming takes place. Once the board is placed underneath the liner and the overlap is sufficient, then the top liner material should be peeled back and the surface prepared for the adhesive.

The specifics of the particular seaming technique must be fully understood by the installer and CQA staff. In the case of some liner materials, e.g., EPDM and CSPE, a surface cure must be removed with a solvent wash prior to seaming. Field crews should have suitable gloves to prevent skin reactions from the solvents. Respirators and eye protection are also recommended. On HDPE membranes, the surface must be physically roughened to remove the surface oxidation layer. Once the surface cure has been removed, the adhesive can be applied to the liner material. With a bodied-solvent adhesive, it is recommended that the two surfaces be placed together immediately and rolled with a steel or plastic roller perpendicular to the edge of the panel. Conversely, contact adhesive systems require that a certain tackiness be achieved before the two surfaces are placed together. Safety and seaming considerations must be carefully reviewed for the particular seaming method used.

The crew should be careful not to allow any wrinkles to occur in the seam. All surfaces should be flat and rolled. It is important, whatever adhesive system is used, that the adhesive be applied uniformly. Some installers recommend that field seaming normally begin at the center of a panel and continue to each end of the seam. This minimizes large wrinkles which could occur if seaming began at one end or the other. In all cases, the adhesive system to be used by the field seaming crew should be that recommended by the manufacturer or a suitable substitute approved for a specific job.

Generally, panels are placed so that field seams will run perpendicular to the toe of the slopes; that is, the seams will run up and down rather than along the side slopes. Perpendicular seams are recommended when side slopes are 4 to 1 or greater in slope. The reinforced materials can be placed so that seams run horizontally on side slopes less than 4 to 1. However, perpendicular seams on side slopes are most often recommended for all cases. This practice minimizes stress on field seams. Corner panels are cut to fit as required, usually pie-shaped from berm to the bottom of the facility.

Installation of liner materials and field seaming during adverse weather conditions require special considerations with respect to temperature limitations. This is particularly true with the thermoplastic materials, since their properties change with temperature. Temperature also affects the rate that solvents will evaporate and the rate that seams become strong. Most manufacturers suggest that their adhesive systems work best when the temperature of the liner material itself is above 60° F. When ambient temperatures are below 60° F and a solvent adhesive system is being used, heat guns can provide an effective means to help bring the temperature of the liner material up to ideal conditions. Extreme caution must be exercised when using heat guns around flammable solvents, which may ignite, and cholorinated solvents which may generate toxic gas.

Cold weather seaming requires that the field crew exercise caution when making seams to assure that the temperature of the liner material reaches minimum acceptable conditions. A cold weather contact adhesive is sometimes used. Field seaming during precipitation must be avoided. Depending upon the location and the weather conditions, the number of panels placed in one day should not exceed the number which can be seamed in one day. This assures that, should bad weather conditions occur overnight, unseamed panels will not be left on the subgrade, subject to damage, especially from wind.

Wind Uplift Forces--

Wind blowing over a geomembrane exerts varying amounts of uplift force depending on the velocity of the wind and the roughness of the surrounding land. When not adequately resisted by sandbags, the membrane will lift off the ground and exert tear stresses on the sheet and seams. Such wind induced stresses have been responsible for numerous failures. Using methods developed by the flat roof industry, some insight into the problem can be gained.

In the absence of site specific data, design wind speeds for the USA are given in Figure 6.2. These values are annual extremes based on a 100-year mean recurrence intervals and represent worst case situations. These contour values are used directly with Table 6.2 to determine the wind uplift value based on elevation above ground and surface roughness. Thus the method is applicable for FMLs placed at the ground level and on elevated caps. For FMLs below grade we recommend a linear extrapolation as demonstrated in Design Example 6.1. It should be noted that the roofing industry recognizes that the perimeter and corners of sheets are the initiating points for uplift and compensate accordingly. For example, they multiply the perimeter uplift forces by 2 and the corner values by 3 for added safety. The temporary nature of a liner installation may not justify such conservatism.

Anchoring--

Proper anchoring of the liner around the facility perimeter, as well as conscientious tailoring and sealing of the liner around penetrating structures, are essential to satisfactory liner performance. Generally, in cut-and-fill type facilities, it is recommended that the liner material be anchored at the top of the dike or berm one of two ways: (1) using the trench-and-backfill method, or (2) anchoring to a concrete structure. The trench-and-backfill method seems to be recommended most often by liner manufacturers, probably due to its simplicity and economy. Excavation of the anchor trench in preparation for laying the liner is usually accomplished with a trenching machine or by using the blade of a motor

Table 6.2 Wind Uplift Forces, PSF (Factory Mutual System)

Height Above Ground, (ft)	Wind Isotach, mph (Figure 6.2)										
	City, Suburban Areas, Towns and Wooded Areas					Flat, Open Country, or Open Coastal Belt>1500ft from Coast					
	70	80	90	100	110	70	80	90	100	110	120
0-15	10*	11	14	17	20	14	18	23	29	35	41
30	10	13	17	21	25	16	21	27	33	40	48
50	12	15	19	24	29	18	24	30	37	44	53
75	14	18	22	27	33	20	26	33	40	49	58

* Uplift Pressures in PSF

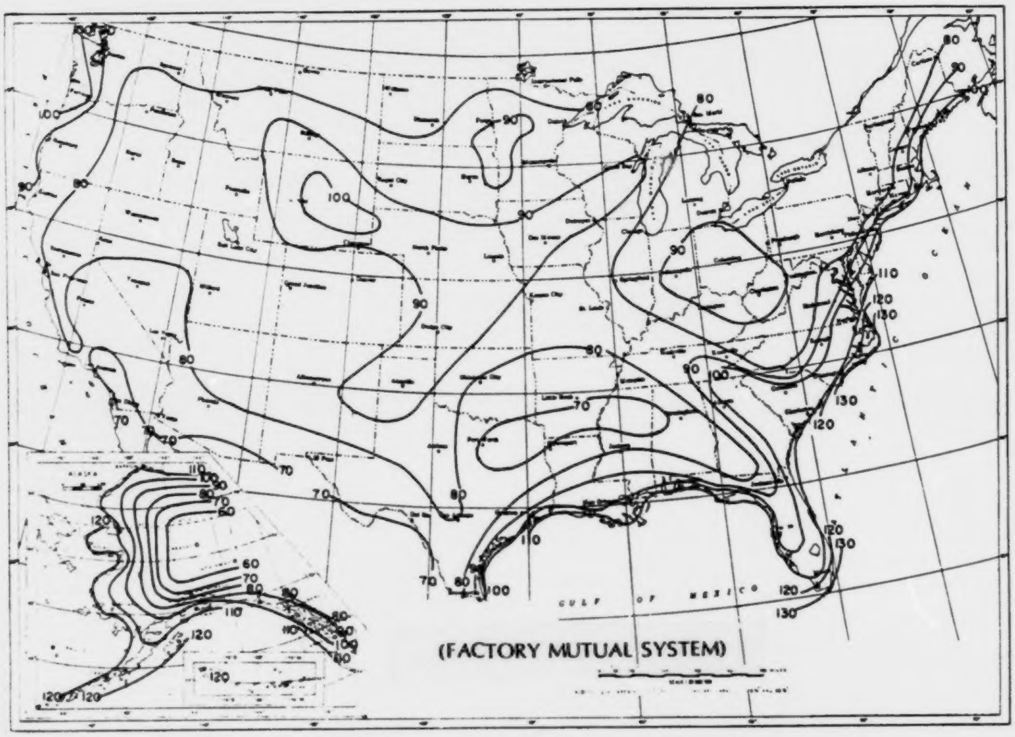

(FACTORY MUTUAL SYSTEM)
GULF OF MEXICO
70
80
90
100
110
120
130

Figure 6.2 Design Maximum Wind Speeds

grader tilted at an angle. Soil from the excavation should be spread away from the anchor pit and smoothed to facilitate unrolling and spotting of panels.

Before opening and spotting the panels, provisions should be made for temporarily, e.g. with sandbags, securing the edges of the liner panels in the anchor trench while the seaming takes place. After the seaming crew has completed the seams for a particular panel, the trench is backfilled with earth that was excavated from the trench. The trench should not be backfilled until after the panels have been seamed so that panels can be positioned for optimum seaming. If the trench (and the edge of the liner) is to be capped with concrete curbing, it is recommended that reinforcing rods be positioned vertically in the trench prior to backfilling. These reinforcing rods can serve to 'nail' the liner to the bottom of the trench while the seaming is done. Care must be taken to prevent puncture of the FML outside of the trench.

The perimeter of the liner may also be anchored to a concrete structure along the top of the berm or dike. This is usually accomplished with anchor bolts drilled or embedded into the concrete and batten strips composed of a material resistant to attack by the chemical(s) to be stored in the facility. Concrete that is to come into contact with the liner should have rounded edges and be smooth and free of all foreign materials to minimize abrasion and chemical interaction with the liner material. Anchor bolts should be positioned not more than 12 inches apart on centers. Concrete adhesive is applied in a strip (minimum width 3-6 inches, depending on the liner material) between the liner and the concrete where the batten strips will compress the liner to the concrete. A strip of lining material (chamfer strip) may be sandwiched between the liner and the concrete wherever the liner material contacts an angle in the concrete structure to prevent abrasion. The batten strips are positioned over the liner material and secured with washers and nuts to the anchor bolts. Mastic should be used to effect a seal around the edge of the liner material. Several alternative methods for anchoring to concrete structures are shown in Figure 6.3 (Koerner, 1986).

Sealing Around Structures/Penetrations--

Depending on the design and purpose of the facility, one or more types of structures may penetrate the liner. These penetrations could include inlet, outlet, overflow or mud drain pipes; gas vents; level indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations may occur in the bottom or through one of the sidewalls, depending upon their function. Because tailoring and sealing the liner around structures can be difficult and offers a possibility for failure of the liner, several manufacturers recommend that over-the-liner pipe placement be used wherever possible. This design facilitates future repairs or maintenance to the piping system and eliminates penetrations.

Penetrations through the liner must be designed so that the object penetrating the liner is either rigidly fixed in its location relative to the liner or so that a flexibility is designed into the connection that allows relative movement of the liner and the penetration without failing the liner. These two types of penetration details are shown on Figure 6.4. The rigid penetration relies on an underlying concrete foundation to fix the location of the penetration. The flexible details in turn rely on slip

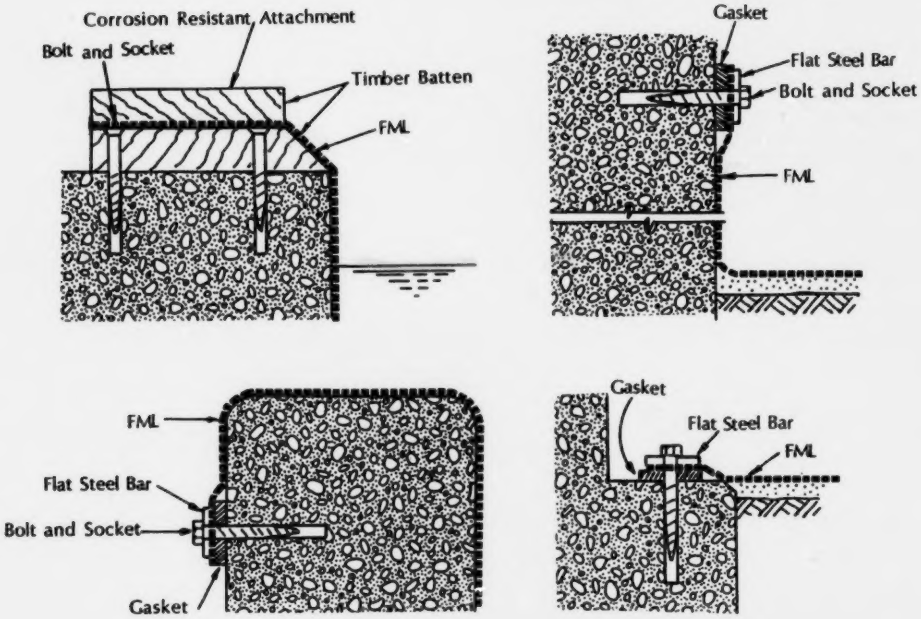


Figure 6.3 FML Anchorage to Concrete - Details

connections fabricated into the boot to prevent tension in the liner. Both details attempt to control the strains generated in the liner from waste settlement induced movements within the liner.

When penetrations through the liner are necessary, most lining manufacturers recommend specific materials and procedures to be used to establish an effective seal around the various types of penetrations. Proper design of the penetrations and selection of an adhesive material that is compatible with the liner are important factors to be considered relative to expected liner performance. For instance, some liner materials are not easily sealed to concrete. Selection of alternative materials may be required. Other materials, on the other hand, may offer optimal conditions for obtaining a good seal; for example, PVC liner can be effectively sealed to PVC pipe using the appropriate solvent to bond the materials together.

Most manufacturers offer standardized engineering designs for: (1) seals made in the plane of the liner, and (2) boots to be used around penetrations. If inlet or outlet pipes are introduced into the facility through a concrete structure, the seal can be made in the plane of the liner. A special liner-to-concrete adhesive system is suggested that is designed for each liner material. Anchor bolts embedded in the concrete and batten strips of stainless steel should be used to secure the liner to the concrete. Mastic should be used around the edges of the liner material to effect a complete seal.

Typically, specialized features such as pipe boots or shrouds are fabricated at the manufacturing facility to design specifications, although they can sometimes be prepared in the field by experienced personnel. Where reinforced membrane liners are being installed, manufacturers sometimes recommend that boots be constructed of unreinforced liner of the same type as that being installed. This allows the slightly undersized boot to be stretched over the appurtenance to assure good physical contact and allows some expandability in case the adjacent liner stretches due to settling. The boot is slipped over the pipe after the main piece of the liner has been cut and fitted around the base of the pipe. The proper adhesive is applied between the pipe and boot and a stainless steel band is placed around the boot where the adhesive has been applied. The base of the boot is seamed to the main part of the liner using the same adhesive system and methods used to make the field seams. Boots should be checked prior to installation to ensure that the angle of intersection with the base is consistent with the angle created between the pipe and subgrade.

Construction Quality Control/Quality Assurance - FML

Competent CQC/CQA inspection is imperative if installation of the FML is to result in a barrier which is effective in controlling migration of leachate to the underlying soils. Placement and surfacing of the subgrade, FML placement and seaming, and sealing of penetrations through the liner require a considerable degree of quality control which should be part of the CQA program assigned to a representative of the facility owner/operator. The representative is required to assure that contractual obligations of the installing contractor and installation specifications are fully met.

Construction Quality Control--

There are three specific areas of quality control concern for the installer in a polymer membrane lined facility. These are the subgrade, FML seams, and sealing of penetrations through the liner. Relative to FMLs, the important subgrade considerations include proper preparation of adjacent soil layers and assuring that no "bridging" occurs in the liner material where angles are formed by the subgrade. Bridging is the condition that exists when the liner extends from one side of an angle to the other, leaving a void beneath the liner at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the bottom of the cell. Installers recommend that particular attention should be directed to keeping the liner in contact with the subgrade at these locations and that it be in a relaxed condition. It is also important to be sure that compaction of the subgrade in these areas meets design specifications to avoid localized stressing of the liner material or seams.

Construction Quality Assurance--

The owner/operator is responsible for establishing a Quality Assurance program to monitor all phases of the FML installation. A knowledgeable representative of the primary facility operator, or representative of the ultimate owner of a lined facility, should be assigned as the quality control agent or engineer on liner installations. The agent will be required to assure that the contractual obligations of the installing contractor(s) are met and that the installation specifications are fully met. Personnel reviewing the design or performing quality control

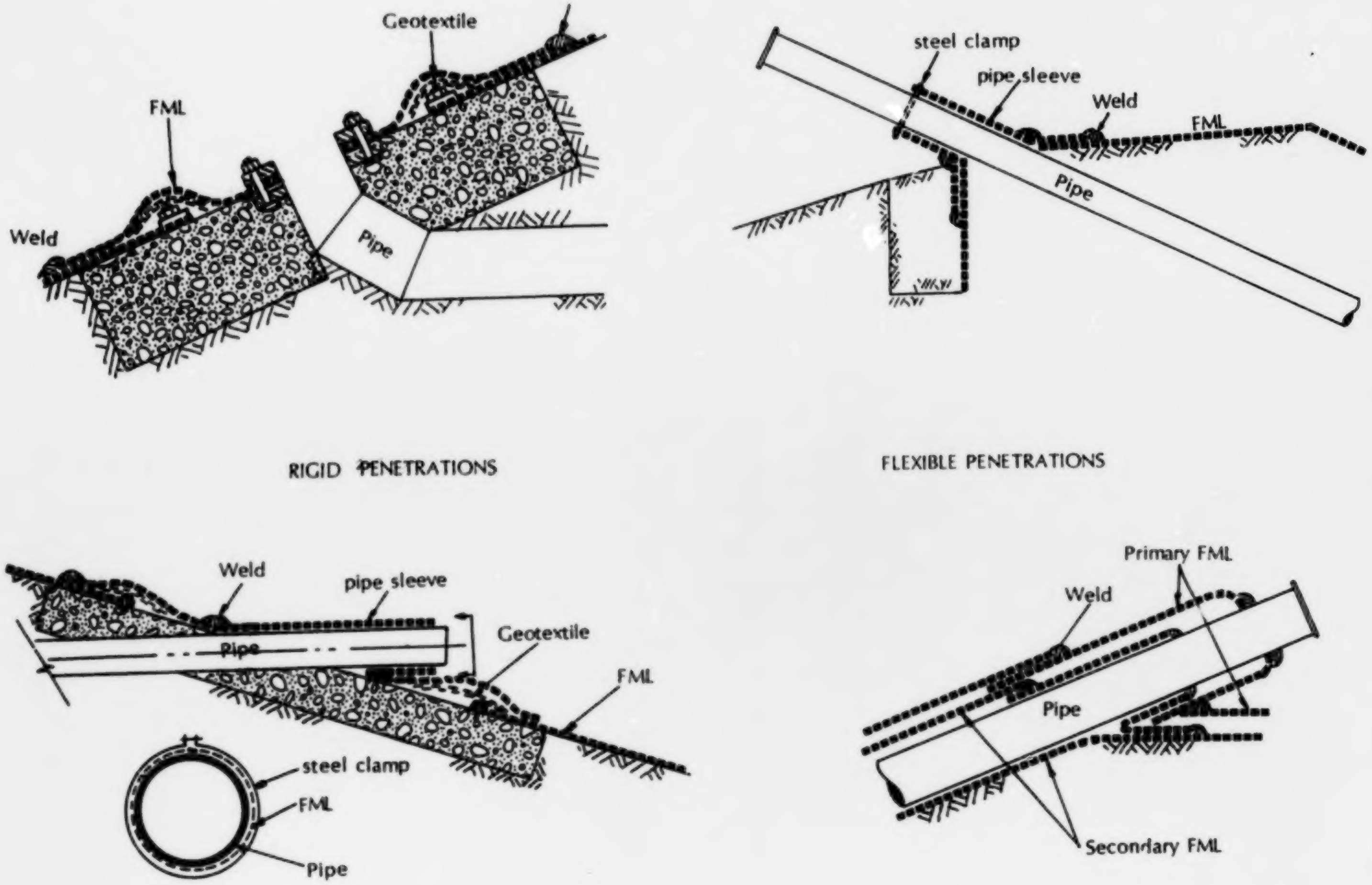

Geotextile
FML
Weld
Pipe
steel clamp
pipe sleeve
Weld
FML
Pipe
RIGID PENETRATIONS
FLEXIBLE PENETRATIONS
Weld
pipe sleeve
Pipe
Geotextile
FML
steel clamp
FML
Pipe
Primary FML
Weld
Pipe
Secondary FML

Figure 6.4 Rigid-Flexible Penetrations - Details

functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the materials' use and installation. This includes everything from the liner's compatibility with the material being stored, to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

Sampling Strategies - General Discussion--
The CQC/CQA programs established to monitor the quality of FML installation must establish reasonable sampling strategies for tests to be conducted on the geomembrane. For the most part, the sampling performed during the manufacture and fabrication is controlled by the CQC programs of the manufacturer and installer. It is not until the FML components reach the jobsite that the owner/operator's CQA program begins to sample the FML. Various strategies exist for determining the frequency of sampling and the acceptance criteria for these tests. These sampling strategies typically fall into one of the following categories:

1) 100-Percent Inspection,
2) Judgmental Sampling, and
3) Statistical Sampling.

It is expected that the CQC/CQA programs for FMLs will involve tests based on all of the sampling strategies. Greater details regarding these strategies are given in the TGD (EPA, 1986a).

The use of 100% inspection must be limited to observations and nondestructive tests. Such inspection may be based on purely subjective evaluation, such as visual inspection, or on actual nondestructive testing, such as the use of a vacuum box to inspect for seam leaks. Examples of 100% inspection include those tests used for FML seams and anchors, collector system pipe joints, pump function, and electrical connections.

Judgmental sampling refers to any sampling strategy where the decisions concerning sampling size, selection scheme, and/or locations are based on nonstatistical methods. The objective may be to select typical sample elements to represent the whole, or to identify zones of suspected poor quality. The frequency of sampling will frequently reflect the confidence that the designer has in the CQA personnel. Judgmental sampling strategies must try and reflect accurately the as-built condition of the facility and yet locate samples in questionable regions. Since the sampling is done on a purely judgment basis, statistical analysis of the data is not practical due to probable bias in the data.

Statistical sampling methods are based on probability theory and are used to estimate specific statistical characteristics, e.g. the mean value, that are used to define acceptance of the construction. The sample selection is based on an objective random process. Selection of this random process is, however, based on experienced judgment. In statistical sampling, a sample unit refers to the smallest unit into which the component in question is divided. For example, the FML could be overlain with a grid with each grid section being a sample unit. The underlying requirement for statistical sampling is that each sample unit must have the same known probability of selection.

There are many variations in sampling strategies possible. A review of those commonly used in facility CQA is given by EPA (1986a). The most common methods include the following:

1) Stratified Sampling - The sampling is based on a weighing scheme that is dependent upon some property of the sample unit.

2) Two-Stage Sampling - Multiple samples are taken from each selected sample unit.

3) Systematic Sampling - Typically involves sampling every n^{th} sample after an initial random start.

4) Simple Random Sampling - Each sample unit has an equal probability of being tested.

Probably the most satisfactory method to the engineer concerned about sampling all parts of the block is a combination of (a) stratified random sampling and (b) systematic sampling with a random start.

Selection of Sample Size - General Discussion--

A statistically rational and valid method of selecting sample size is given in ASTM (Annual) Designation E-122, "Standard Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process." The equation for the number of units (sample size, n) to include in a sample in order to estimate, with a prescribed precision, the average of some characteristic of a lot is:

$$n = (ts/E)^2 \qquad \text{Eq(6-1)}$$

or, in terms of the coefficient of variation

$$n = (tV'/e)^2 \qquad \text{Eq(6-2)}$$

where

n = number of units in the sample
t = a probability factor from the Student-t Tables
s = the known or estimated true value of the universe, or lot, standard deviation
E = the maximum allowable error between the estimate to be made from the sample and the result of measuring (by the same methods) all the units in the lot
V' = coefficient of variation = s/X , the known or estimated true value of the universe or lot e = E/X, the allowable sampling error expressed as a percent (or fraction) of X
X = the expected (mean) value of the characteristic being measured.

The probability factor, t, corresponds to the level of confidence that the sample expected value will not differ from the actual value by more than the allowable difference, E. A sample size needed to estimate the reliability of the overall material will not be small enough to be used to assess the quality of a subsection.

Typical FML CQC/CQA Programs--

Field quality control/assurance testing of FMLs is focused on the quality of seams produced in the field. Installers will usually base their field CQC program on periodic destructive testing of sample welds made on FML sheeting similiar to that being installed, and on 100% nondestructive seam testing using a vacuum box. The destructive testing is not on seams that are part of the actual facility, but are prepared on a periodic basis specifically for testing. The frequency that destructive samples are prepared varies from the beginning, and end of an 8-hour shift to as frequently as every 3 hours. The installers quality control test program is designed to verify the continuity of the seams using 100% testing and the strength of the seams using a statistical periodic sampling program. The major objection to the program is that the seam strength samples are prepared specifically for testing and may not be representative of the FML seams. Destructive testing of actual FML seams occurs every 500 to 1000 feet of seam and on a judgmental basis if soil or water are suspected of contaminating a seam.

The Construction Quality Assurance (CQA) program of the owner/operator is typically built on a statistical program of both destructive and nondestructive testing. These programs are normally based on statistical methods of sampling that base the number of tests on the performance of previous tests. For example, the minimum number of tests of a given lot using Equation 6.1 is based on the standard deviation of the actual lot. While this number must be initially estimated, the estimate can be revised on a regular basis using the data obtained from previous destructive samples from all lots. This can be demonstrated by examining a typical sampling program for destructive testing of FML seams. Initially the sampling program could be based on Equation 6.1 with the following assumptions:

- $t = 1.97$ (95% confidence level)
- s = estimated standard deviation
  = 10% of mean
- E = allowable error set at 10% of mean

Substituting these values into Equation 6.1 indicates that four tests per lot are required. Here a lot may be defined as the welds performed during a given shift. During the course of the installation, the destructive tests performed can serve as a basis for a revised estimate of the standard deviation. Thus if the seam quality is poor, the standard deviation will increase and the number of destructive CQA tests required will increase.

For seams that fail, the MTG recommends that the seam be reconstructed between the failed and any previously passed seam location. If this is an excessive length, then the installer can go 10 feet on either side of the failed test, take another sample, and if it passes reconstruct the seam between the two locations. In all cases, the reconstructed seam must be bounded by two passed test locations.

While the installer has performed a 100% nondestructive test of the seams, it is not unusual for the CQA program to require a percentage retesting of all seams using a longer dwell time for the vacuum box test. Typical dwell times used by installers in performing the vacuum box test are 10-15 seconds at a vacuum of 2.5 psi. CQA vacuum tests may require dwell times exceeding 90 seconds. These longer dwell times must be used with caution because they can put excessive strains on thin liners. As with destructive testing, the CQA program should provide a systematic method for increasing the percentage of nondestructive testing based on the percentage of failures found in the CQA testing. Some of the NDT tests previously shown on Table 6.1 can provide 100% testing of the seams to supplement the standard vacuum tests.

Maintaining clear records of installation and testing is an important part of the CQA program. The record systems typically utilize the seam and panel numbering systems previously shown on Figure 6.1. These records will typically include the following forms:

1) Panel Placement Log
2) Geomembrane Seam Test and Inspection Log
3) Geomembrane Repair Log

The panel placement log, Figure 6.5, documents the condition of the subgrade, weather, and panels during the installation of a given panel. This log may enable the CQA officer to find a common cause of panel seam problems, e.g. cold temperatures. The next form chronologically is the geomembrane seam test and inspection report shown on Figure 6.6. This log records the results of the seam tests and notes any defective seams requiring repair and further testing. The final log is shown on Figure 6.7 and records the repairs made to the defective seams. Each CQA officer must establish a system of logs to document the correct installation of the liner. The logs presented here are intended only for guidance in development of such logs. A particularly attractive aspect of ultrasonic testing methods is their ability to record continuous, hard-copy of the results of the inspection, see Table 6.2.

Table 6.3 Overview of Nondestructive Geomembrane Seam Tests after Koerner and Richardson(1987)

Nondestructive Test Method	Primary User			General Comments					
	Contractor	Design Engr. Insp.	Third Party Inspector	Cost of Equipment	Speed of Tests	Cost of Tests	Type of Result	Recording Method	Operator Dependency
1. air lance	yes	-	-	$200	fast	nil	yes-no	manual	v. high
2. mechanical point (pick) stress	yes	-	-	nil	fast	nil	yes-no	manual	v. high
3. vacuum chamber (negative pressure)	yes	yes	-	$1000	slow	v. high	yes-no	manual	high
4. dual seam (positive pressure)	yes	yes	-	$200	fast	mod.	yes-no	manual	low
5. ultrasonic pulse echo	-	yes	yes	$5000	mod.	high	yes-no	automatic	moderate
6. ultrasonic impedance	-	yes	yes	$7000	mod.	high	qualitative	automatic	unknown
7. ultrasonic shadow	-	yes	yes	$5000	mod.	high	qualitative	automatic	low

PANEL PLACEMENT LOG

Panel Number ______

Owner: ____________________ Weather: ____________________

Project: ____________________ Temperature: ____________________

Date/Time: ____________________ Wind: ____________________

Subgrade Conditions

Line & Grade: ____________________

Surface Compaction: ____________________

Protrusions: ____________________

Ponded Water: ______________ Dessication: ______________

Panel Conditions

Transport Equipment: ____________________

Visual Panel Inspection: ____________________

Temporary Loading: ____________________

Temp. Welds/Bonds: ____________________

Temperature : ____________________

Damages: ____________________

____

Seam Details

Seam Nos.: ____________________

Seaming Crews: ____________________

Seam Crew Testing: ____________________

Notes: ____________________

____

____

Figure 6.5 Panel Placement Log

GEOMEMBRANE SEAM TEST LOG

				CONTINUOUS TESTING		DESTRUCTIVE TEST				
SEAM No.	SEAM LENGTH	VISUAL INSPECT	AIR TEMP.	TEST METHOD	PRESSURE INIT/FINAL	PEEL TEST	SHEAR TEST	LOCATION	DATE	TESTED BY

Figure 6.6 Geomembrane Seam Test Log

GEOMEMBRANE REPAIR LOG

DATE	SEAM	PANELS	LOCATION	MATERIAL TYPE	DESCRIPTION of DAMAGE	TYPE OF REPAIR	REPAIR TEST TYPE	TESTED BY

Figure 6.7 Geomembrane Seam Repair Log

DRAINAGE/FILTRATION COMPONENTS

The leak collection and removal system is designed to drain liquids accumulating in the liner system. Conventional leak collection systems consist of a 1-foot-thick granular media immediately overlying the hydraulic barrier. The ability of this system to drain away moisture is enhanced by constructing the system at a minimum slope of 2%, and by using permeable sands or gravels that are free of fines. Geosynthetic components within a conventional LCR system are usually limited to the possible use of a geotextile bedding layer over the underlying FML, and the use of a filter fabric to separate the drainage media from the overlying clays. Totally synthetic LCR systems replace the layer of gravel or sand with a layer of geonet or a heavy nonwoven geotextile having equivalent planar flow properties.

Several key differences exist between the procedures used for placement of the FML and those used for synthetic components within the LCR. Unlike the FML, the LCR components are typically placed by the general contractor responsible for the overall construction of the facility. This contractor may not show the same expertise in the placement of LCR components that the specialized manufacturer/installer has in the placement of the FML. Thus it is important that the CQA officer play a greater role in monitoring the quality of LCR components. The geonets,geocomposites, and geotextiles used in the LCR are also normally frequently fabricated in the field during installation. A given roll of drainage net may therefore not have a unique location in the facility. The CQA officer will therefore have a greater responsibility to monitor and record the placement of these components by roll or manufacturer's lot number.

Specifications

The project specifications must clearly indicate the required design performance criteria for the potential drainage and filtration components. While the variations in synthetic materials to be used is considerable, the basic requirements are very simple. These requirements include:

1) All synthetic compounds must be inert and unaffected by long-term exposure to potential leachate or design loads.

2) Drainage materials must satisfy minimum TGD criteria under the normal loads predicted for the specific facility.

3) Filtration materials must not clog or blind due to the fines contained in adjacent soils.

4) Adhesives or hot glues used to adhere the various synthetic components together must not contribute constituents to the leachate.

5) All connections must be made using the same polymer system as is used for the geomembrane seams themselves.

These criteria are design-oriented and not readily field tested or evaluated. The project specifications may therefore define criteria that are not readily verified by the CQA procedures. It is usually necessary for the CQA officer to establish index tests for each component to ensure that installed materials are the same as those prequalified in actual laboratory tests.

Component Qualification--

The prequalification of a given synthetic product is normally the responsibility of the manufacturer. Appropriate laboratory tests must be performed on each component using actual site-specific soil samples provided by the design engineer. The results of such testing and a sample of the synthetic material are normally submitted to the design engineer for approval prior to bidding the project. Confirmation tests are performed at the discretion of the design engineer. Design-oriented testing performed on LCR components includes the following:

1) Drainage materials must have a minimum transmissivity of 0.02 ft^2/minute at gradients less than 1 and under normal loads anticipated in actual service. Consideration of long-term compressive creep should be addressed in this testing.

2) The clogging or blinding potential of geotextiles used in filtration must be evaluated using the gradient ratio method or an approved test.

3) The frictional strength between a geosynthetic component and its adjacent soil or synthetic component is evaluated using a large size direct shear test. A minimum shear box size of 12"x12" is recommended.

4) Tensile strengths should be evaluated using wide-width test procedures for geotextiles or geonets.

These tests are not suited for field CQA needs. Once a geosynthetic material is qualified based on its design properties, then index test properties for that material must be established to ensure that it is not replaced by an inferior product during construction. These properties include unit weight, thickness, tensile strength, trapezoidal tear, puncture and color. Such index properties serve as a fingerprint of the qualified material and enable the CQA officer to monitor field installation.

Delivery and Storage--

Geotextiles, geocomposites, and geonets are typically shipped to the job site in rolls. Project specifications must require that each roll be protected with a covering that prevents physical damage, contamination by dust or water, and exposure to direct sunlight. The specifications should also require that each roll be identified with the following mimimum information:

1) Name of manufacturer/fabricator,
2) product type,
3) product unit weight,
4) manufacturing lot number,

5) date of manufacture,
6) physical dimensions (length and width),and
7) panel number per design layout pattern if applicable.

The site CQA officer should inspect each roll to ensure compliance with these specifications and maintain a record of all roll identification tags.

Project specifications should require that all geotextiles delivered to the job site be stored in a secure area that protects the rolls from vandalism by man or animal, contamination by soil, dust or water, and from extreme heat caused by direct sunlight. An example of such a problem is when a heavy geotextile drainage material becomes saturated by rainwater. The unit weight of the material can triple causing considerable difficulty is placing the material without damaging it or underlying components.

Installation--

Installation specifications for geosynthetic components in the LCR system must ensure that the completed LCR drains properly and that it will remain free-flowing for the design life of the cell. The drainage of a synthetic LCR is influenced by both vertical and horizontal alignment and folds or wrinkles in the underlying FML. The drainage characteristic of a conventional 1-foot-thick drainage layer is not significantly influenced by the presence of folds or wrinkles in the FML. Synthetic drainage layers, however, are less than an inch in thickness. Thus significant folds or wrinkles in the underlying FML can actually lead to a reverse flow in the as-built system. Project specifications must clearly indicate the accuracy to which the alignment must be maintained and the amount of wrinkles or folds allowed in the FML. Excessive wrinkles or folds are usually corrected by cutting the FML, overlaping the edges of the cut, and then seaming the exposed edge of the cut.

Project specifications should also clearly indicate the joining details for both drainage and filter components. Drainage media may simply require butting adjacent panels together whereas a material overlap is normally required for filtration layers. Geonets are typically joined using polyethelene ties to bind butted panels together. If a composite drainage-filtration component is used, then the filter fabric may be heat bonded to join adjacent panels. Horizontal seams in the drainage media should be avoided on sideslopes because of the reduced tensile strength of such joints. A minimum overlap of a filter fabric 12 to 18 inches is commonly used to prevent movement of fines into the drainage core.

Sampling and Testing--

Synthetic components for the LCR systems are normally installed by the general contractor responsible for construction of the facility and not a specialized manufacturer/installer. The general specifications should not require the general contractor to perform index tests on the material. The specifications should require the general contractor to maintain a record of the manufacturer's data that accompanied each roll and to perform a visual inspection of the material to check for obvious damage or variation in material.

The responsibility to perform index tests and obtain samples of the LCR materials should be maintained by the CQA officer for the facility. This is discussed in greater detail within this section.

Construction

Construction of a leak collection/detection layer should extend up the sidewalls. The advent of synthetic drainage nets has resulted in many facilities being constructed with the synthetic systems on the sidewalls and having bottom drainage layers of granular material and drain pipes. Synthetic drainage net material is often used on the sidewalls in place of the granular system because it is easy to install on steeply sloped sidewalls. Steep sidewalls cause the granular drainage material to slump down, whereas the synthetic drainage material tends to remain in place. An obvious fabrication rule is to avoid horizontal seams in the synthetic LCR systems on the sideslopes. All seams are capable of only a portion of the tensile strength of the parent sheeting and should be avoided when the synthetic will experienced prolonged tensile forces.

A conventional leachate collection/removal system is installed in the following manner: A layer of granular material (about 5 cm thick) is spread over the underlying layer (e.g., an FML). The protective soil covering should be comprised of material which is free of clods, stones or other sharp objects that can puncture the FML. If the underlying layer is an FML, the granular material will provide protection for the FML as well as bedding for the drain pipes. The perforated pipes are then laid on this layer according to the drainage layout in the design specification. In most cases, perforated pipes of four to six inches in diameter are used. The perforations in the pipe should be faced downward to prevent clogging from the drainage material. After placing the pipes, the remaining granular material is spread over the area in a single loose lift to the required thickness and compacted with a vibratory roller into a firm base for the primary FML.

If synthetic drain panels are used, they should be unrolled and spotted as in FML installation, however, the panels are not overlapped and seamed. They should be placed end to end and connected according to the manufacturer's suggested procedures, with the lower portion of the panel extending into the granular or other bottom layer to enhance continuity between the drain layers. A geotextile filter should be placed on top of the drain panels to prevent clogging due to infiltration of fine materials from above. The synthetic drain system should be secured in the anchor trench as in the FML installation.

Construction Quality Assurance

As discussed earlier, the CQA program plays the role of monitoring the installation of geosynthetic components within the LCR. Each filter or drainage component is usually accepted based on design tests that are not reasonable for use in field CQA applications. The design engineer must therefore provide the CQA officer with a 'fingerprint' of the accepted material that uses simple index tests as a basis for acceptance. Additionally, since these components are typically fabricated in the field, the CQA officer must establish a record keeping system that records the final location within the facility of all inventoried rolls.

As a practical consideration, it is important that the CQA officer be provided samples of each of the components that are known to satisfy the design criteria. With these reference 'standards' the CQA officer has a basis for evaluating general field observations. It is also recommended that the CQA officer inventory and obtain a sample of each roll of geosynthetic that is received at the jobsite. These samples should be marked to identify the machine direction and tagged with the manufacturers roll information. An alternative to sampling every roll is the geotextile sampling strategy given by ASTM D4354. This strategy samples a limited number of rolls within a given lot designation. The number of rolls sampled is a function of the total number of rolls in the lot.

Filtration Fabric Index Tests--

Filtration fabrics function to allow leachate to pass into the drainage materials and to minimize the movement of soil particles through the plane of the fabric. As such the size of the pore spaces (or Apparent Opening Size) and permittivity of the fabric are key physical properties. The problem is that the AOS and permittivity of a geotextile are not ready field indexes. Assuming that the correct polymer, fabric construction (e.g. nonwoven), and surface finish are used, the use of unit weight should provide a reasonable control for filtration fabrics. Care must be taken to properly precondition the fabrics before measuring unit weights to eliminate descrepancies due to variations in water content. Oven drying the fabric samples in the same manner that soils are dried (ASTM D-2216) is recommended.

Geosynthetic Drainage Material Index Tests--

Geosynthetic drainage components include geonets, geocomposites, and thick geotextiles. The physical structure of the geonets and composites is large enough that a visual comparison with the 'standard' maintained by the CQA officer and a comparison of unit weights and/or thickness should provide adequate quality assurance for these components. As with geotextiles, care should be taken to precondition the samples prior to obtaining unit weights to eliminate variations in moisture content. The thick nonwovens used as drainage layers pose a more difficult problem to properly 'fingerprint' using index tests. These materials will normally be a composite that includes the filtration layer and the drainage layer. Field testing of such nonwovens will typically be limited to unit weight as recommended for filtration fabrics.

SUBGRADE

General industry suggestions are very similar regarding subgrade characteristics. For an earthen structure, the subgrade must be firm and dry, free of all rocks, roots, debris, or other objects that might tear or puncture the liner. Excavation and backfilling are recommended if necessary to meet these conditions. Where vegetation has been cleared to prepare the site, or soil has been brought in to provide a bed for the liner, soil sterilization may be specified to prevent grasses from growing through the liner. This is especially true in areas where prior growths of nut or quack grasses have existed. Areas where excavated soil is deposited to create subgrade may also require sterilization. Care must be taken in soil sterilization since most sprays used for such applications are highly toxic and are hazardous by themselves. Compatibility of any synthetic component that will contact the sterilized soil should be verified. A survey of current methods of constructing compacted soil liners by Elsbury (1985) identifies processing, placement, and compaction required to construct a suitable soil liner.

Specifications

With regards to geosynthetics within hazardous waste facilities, the major concerns regarding soils are that they provide adequate support to the synthetic component and that they are free of rocks or other objects that could damage adjacent geosynthetics. The support characteristics of the subgrade are normally covered in the project specifications by requiring a given percentage compaction of the soil beneath secondary FML and the drainage media below the primary FML.

Construction

Compaction of the subgrade is normally specified to provide a firm support for all membrane lining materials. Generally, a fill subgrade is compacted only at the surface. Usually, the minimum compaction of the subgrade material will be specified. Most liner installations specify that the density of the subgrade be at least a specified percentage of that obtainable by the Standard Proctor Test, ASTM D698, with 90 percent of Proctor being the most frequently specified relative compaction. Some contracts will specify the compaction equipment which is to be utilized, number of equipment passes per layer, layer thickness, permissible water content range at placement, and method and location of water addition.

The regularity and texture of the surface of the uppermost layer is critical to a successful liner installation. A plane surface after compaction is the most desirable one for liner placement but is not always achievable or specified in the contract. In many installations, soil clods or local surface irregularities will be flattened (further compacted) by the overlying weight of the stored material after the facility is filled. Further, it is thought that the polymeric membrance liners will adjust their shape over any clods so that no detrimental effects will result. Nevertheless, rocks or irregularities with sharp edges must be eliminated from the finished subgrade during the compaction/construction process even when not specified in the contract if liner integrity is to be maintained.

Within the polymeric membrane liner industry, there is a difference of opinion as to how smooth surfaces must be to maximize liner integrity. The opinions vary with the liner material. It is generally agreed, however, that the smoother the finished surface, the chance of liner failure due to subgrade inadequacies is reduced.

Fine Finishing of Surface--

If compaction has been accomplished with a sheepsfoot compactor, it is normal to fine-finish the surface. Fine-finishing is an intensive aspect of subgrade preparation. Depending on the design specifications, various techniques are recommended. A smooth surface on the bottom and sidewalls can be accomplished with various drags which aid in the formation of a regular, flat working surface. Fine-finishing with vibrating rollers and drags is recommended on a slightly wet surface; thus, water tank trucks may be required during the fine finishing activities. Occasionally, soil additions are required to bridge surface irregularities if the irregularities cannot otherwise be removed. Sand is useful for this purpose as it is easily compacted.

The fine-finishing process is critically dependent on the proper care and control of water. If rain occurs during or immediately after the fine finishing work on a slope, small brooks, ruts, ravines, etc., may be eroded into the surface. Thus,the expenditure of effort to fine-finish slopes and bottoms for subsequent membrane liner placement is not recommended when rainfall is imminent; conversely, the placement of liner material on fine finished slopes is recommended as soon after completion of "finishing" as possible to ensure that no surface soils are "lost" to the erosive effects of surface runoff. During the fine-finishing stage, any grasses and other vegetation must be removed from the subgrade layer to prevent their penetration into the FML layer. Timing between activities is critical in maintaining proper moisture content of the subgrade; therefore, the FML should be placed on the finished subgrade as soon as possible after completion of the finishing process.

Construction Quality Assurance

The construction quality assurance program for the placement of the soil liner under MTG (EPA,1985) begins with the construction of a test fill to establish the relationship between the index properties used to monitor construction and the physical soil properties used in the design. EPA guidance provides the following guidance for test fills:

1. Construction of the test fill should use the same materials, equipment, procedures, and CQA to be used in the actual facility;
2. The test fill should be at least four times wider than the widest piece of equipment to be used in construction;
3. The test fill should be long enough to allow construction equipment to reach normal operating speeds before entering the test fill;
4. Construction data should be used to determine the relationship of field test results (moisture content/density/hydraulic conductivity) to the compaction method, equipment speed, and loose and compacted lift thickness; and
5. A set of index properties should be selected for monitoring and documenting the quality of construction obtained in the test fill.

During placement of the subgrade, a documented program of measuring and logging the index tests in the subgrade must be implemented. Details of such a program are presented elswhere (EPA, 1986a).

Between the time that the subgrade is placed and the FML is installed, the condition of the subgrade can deteriorate. The panel placement log requires the installer to approve the subgrade prior to placement of the liner. This approval is typically based on a visual inspection of the subgrade for surface quality and the use of proof rolling to establish the strength of the subgrade. Proof rolling may simply be monitoring the rut depth produced by construction related equipment passing over the site. Excessive rutting indicates that subgrade soils have been disturbed and require replacement before the liner is installed.

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Cell Component: FLEXIBLE MEMBRANE

Consideration: WIND LIFT: CALCULATE THE REQUIRED SANDBAG SPACING FOR FML/FMC PANELS DURING PLACEMENT.

Required Material Properties	Range	Test	Standard
FLEXIBLE MEMBRANE • UNIT WEIGHT	3-20osy	DENSITY	ASTM D792

Draft MTG Minimum

Analysis Procedure:

(1) DETERMINE DESIGN MAXIMUM WIND SPEED, V_{WIND}

• USE SITE SPECIFIC DATA OR REFERENCE FIG 6.2

(2) DETERMINE WIND-UPLIFT PRESSURE, P_{WIND}

• REFERENCE TABLE 6.2 W/ $V_{WIND} \rightarrow P_{WIND}$

NOTE: PERFORM LINEAR INTERPOLATION FOR DEPTHS < 0 FT

(3) CALCULATE SAND BAG SPACING

• W_S = WEIGHT OF SANDBAG

• TRIBUTARY AREA = P_{WIND}/W_S = TA

(4) CALCULATE DESIGN RATIO

$$DR = TA/[\text{ACTUAL FIELD TRIBUTARY AREA}]$$

Design Ratio:

DR_{MIN} = 1.1 (SHORT-TERM ONLY)

References:

FACTORY MUTUAL SYSTEM

Example:

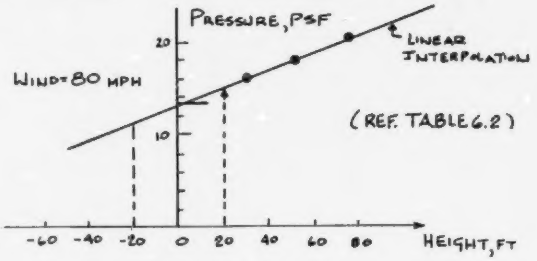
GIVEN:

- PHILADELPHIA, PA
  - ANNUAL EXTREME WIND SPEED (FIG 6.2)
    V_{WIND} = 80 mph
- WIND = 100 YR EXTREME, OPEN COUNTRY
- FML DEPTH = -20 to +20 FT.
- SANDBAG = 80 lb. @ 1 PER 10 SQ.FT.
- HEIGHT TO FM = -20 FT, 0 FT, +20 FT

(1) DETERMINE DESIGN MAXIMUM WIND SPEED, V_{WIND}

V_{WIND} = 80 MPH (REF FIG 6.2)

(2) DETERMINE WIND UP-LIFT PRESSURE, P_{WIND}



DEPTH -20 FT → 11 PSF
0 FT → 14 PSF
20 FT → 15 PSF

(3) CALCULATE SAND BAG SPACING

-20 FT → 80 lb/11 PSF = 7.3 SQ.FT.
0 FT → 80 lb/14 PSF = 5.7 SQ.FT.
+20 FT → 80 lb/15 PSF = 5.3 SQ.FT.

(4) CALCULATE DESIGN RATIOS

-20 FT. → 7.3/10.0 = 0.73 NG
0 FT → 5.7/10.0 = 0.57 NG
+20 FT → 5.3/10.0 = 0.53 NG

Example No. 6.1

SECTION VII

LONG TERM SERVICE CONSIDERATIONS

This section of the report brings into focus the fact that solid waste disposal facilities must be designed with long-term service considerations in mind. Up to this point in the report, the focus has been on immediate, or short-term, events and phenomena. Now, time frames of 30 to 50 years (some people suggest much longer) must be envisioned. Hence, chemical, biological, thermal and general aging deterioration of the liners and their leachate collection/removal systems must be considered. Unfortunately, quantifiable design methods for long-term concerns are usually not available. Thus this Section is written on a qualitative basis. Whenever possible, specific data and information will be offered. The section is divided into three parts: the FML's, LCR's, and the cap/ closure system.

FLEXIBLE MEMBRANE LINERS

Of foremost importance with the liner themselves is the long-term effects of leachate on polymeric materials from the leachate within the containment cells. This includes both the primary and secondary FMLs on both bottom and sides of the facility. Schnabel (1981) defines polymer degradation as changes in physical properties caused by reactions involving bond scission. Bond scission may be initiated by chemical, photochemical, biological, thermal, mechanical, and radiation stimuli.

Chemical Attack

As noted in the Introduction, chemical degradation and its testing protocol is beyond the report scope. It is, however, foremost in importance and, as such, covered elsewhere in various EPA documents, e.g., see Matrecon(1987). It should be brought to mind, however, that the current testing protocol via EPA 9090 Method is focused on highly concentrated leachate exposure at elevated temperatures for very short periods of time, e.g., for 120 days. It begs the question as to the influence of low-concentration, ambient temperature, and long-exposure effects on the liner, where a sparsity of information is available. Clearly, research is needed in this regard.

The main mechanisms involved in chemically induced bond scission insofar as thermoplastic materials like PVC, CPE, HDPE, etc, are concerned as follows:

- Metathese - breaking of carbon-to-carbon bonds
- Solvolysis - breaking of carbon-to-noncarbon bonds in the amphorous (liquid phase)
- Oxidation - liquid reaction with molecular oxygen
- Dissolution - separation into component molecules by solution.

Obviously, when taken either separately or collectively, the above mechanisms will have a negative effect on the FML's ability to function properly.

One approach which has been taken to evaluate chemical mechanisms is that of accelerated aging at elevated temperatures. By obtaining a reaction energy between two test specimens at different temperatures and using an analytical model, e.g., Arrhenius modeling, it is possible to obtain a long-term projection of the equivalent time exposure. The Arrhenius model assumes that the the rate of chemical reactions is given by

$$K^t = R^t/C \qquad \text{Eq(7.1)}$$

where K^t is the rate constant at temperature (t), R^t is the measured rate of change of a chemical component, and C is a constant. The rate constant is a function of temperature according to the Arrhenius equation

$$K = Ae^{-E/RT} \qquad \text{Eq(7.2)}$$

where A is a constant, E is the reaction activation energy, T is temperature (^{o}F), and R is the gas constant. See Koerner and Richardson (1987) for a numeric example of this procedure.

This procedure is however, not without its limitations and challenges and must be further assessed for its validity and usefulness. Studies by Mitchell and Cuello (1986) indicate that immersion tests such as EPA 9090 give similiar results and are much less expensive. They felt that the added cost and complexity of the accelerated aging test did not appear to be warranted.

Photochemical Attack

Photochemical attack of polymers is caused by ultraviolet (UV) light that foster oxidation of the polymer. UV resistance in polymers is normally achieved by adding a low (<5%) percentage of carbon black to the polymer to make the membrane opaque. Accelerated testing of photochemical aging is performed by focusing mirrors on the test specimens to concentrate the sunlight. As this also generates significant heat, it is normally necessary that the specimens be sprayed with water to cool them. This test is referred to as EMMAQUA, equitorial mount with mirrors plus water spray. The method normally accelerates the solar exposure by a factor of 8.

EMMAQUA test results reported by Morrison and Parkhill (1986) indicate that thermal degradation of samples typically occurred after 6 months of exposure. HDPE samples actually melted during this exposure; indicating that the degradation may have been more thermal than photochemical. This work also suggests that the current NSF Standard 54 EMMAQUA requirement for certifying new FML's may also be too severe. The NSF standard requires the equivalent of eight months of EMMAQUA exposure.

Ozone Attack

Ozone, a powerfully oxidizing form of oxygen (O_3), attack of FML's has been recognized as a potential problem as evidenced by the number of ASTM test standards directed towards its evaluation. All currents tests, however, seem to focus on thermoset membranes. Such tests include ASTM D518 (general rubber deterioration), ASTM D1171 (surface ozone cracking outdoors), and ASTM D1149 (surface ozone cracking in a chamber). In this latter test, the specimens are placed under a tensile stress or strain in a chamber containing an ozone-air atmosphere at a controlled and prescribed temperature. The ozone concentration can be varied and is measured by a spray-jet device or a single column absorption device. The test specimens are examined at given time intervals and their condition recorded. Failure is caused by surface cracking in the high stress or strain region as observed under a slight magnification. Test method ASTM D 1171 recommends a 2X magnification, while ASTM D1149 recommends a 7X magnification. When comparisons are being made to a given reference material, they are usually made at fixed time intervals with the comparison based on the degree of cracking.

Biological (Micro-organism) Attack

The microbiological degradation of FML's by micro-organisms such as fungi and bacteria has received very little attention. Clearly, solid waste has a great abundance of micro-organisms, some of which are detrimental to certain plastic products. It is likely that the more organic the waste, the more active will be those micro-organisms. The focus of biological problems with FML's is that once the bacteria or fungi has attached themselves to the synthetic or natural material adjacent to the liner they will eventually use it for a food source. This would be disastrous to the integrity of the FML. Current research is directed towards developing synthetic systems that resist the growth of such micro-organisms. Microbes may be placed in four categories;

- o Bacteria (weight may exceed 1,000 pounds per acre for soil)
- o Fungi (One gram of soil commonly containing 10 to 100 meters of mould filament)
- o Actinomyces (one gram of soil containing 0.1 to 36 million)
- o Algae (a number of varieties exist).

The premier reference in this area is an in-house research report by Khan of ICI, as reported by Rankilor in 1981. The summary table is reported below (See Table 7.1) in which it can be seen that all plastics suffer some deterioration. It also must be remembered that these results are for soil microbes which might well be less numerous and less harmful than those resulting from solid waste in a landfill.

Research has been conducted by the electric transmission line industry for buried plastic conduits. Rankilor (1981) reports on some of this data where severe degradation has not occurred --- at least by micro-organisms.

Table 7.1 - Micro-biological Attack on Plastics, after Rankilor (1981)

Material	Observations on susceptibility
1.Nylon	The material contains polypeptide linkages, and it might be supposed that microbiological attack is highly probable. According to Russian work, nylon suffered from a change of color and a weakening of the film due to microbiological attack, particularly by Penicillium and Aspergillus.
2.Polyester	Microbial degradation of the material was reported by several investigators. Potts, et al (1973) found biodegradation of polyesters of varying structure and molecular weight (a group of fungi and bacteria used as test organisms). They found that an epsilon caprolactone polyester of about 40,000 molecular weight, which had no branch, was readily utilized by fungi and bacteria.
3.Poly-ethlylene	The material shows a good resistance to microbiological attack, especially when pigmented with carbon black. The US Navy Department observed that the material of lower molecular weight supported microbial growth, this being in agreement with the work of Jen-Hao and Schwartz. Potts, et al, found that some of the LDPE having molecular weight between 10,000 to 14,000 was appreciably biodegraded. They attributed this effect to the presence of low molecular weight species (<500 mol wt.).
4.Poly-propylene	The material shows good resistance to microbiological attack. Potts, et al, (1973) observed biodegradability of a large number of commerical plastics including polyprolylene (a group of fungi and bacteria were used as test organisms). The microbial growth was thought to be due to the presence of a biodegradable additive in the sample.
5.Polyvinyl	The overall conclusion from several experiments is that the material, rather than the polymer itself, is directly attacked by microbes, particularly fungi. Hueck (1973) reported discoloration of the PVC materials and precipitation of FeS by sulphate reducing bacterial. Schwartz investigated a range of chlorinated lower paraffins of increasing chlorine content, and showed that bacteria could use these easily as a source of carbon up to chlorine content of 30%, above which growth rate slowed down and became non-existent at 50% (PVC and vinyl chloride monomer have <50% of chlorine).
6.Poly-styrene	The material shows a fair amount of resistance to microbial attack. Potts, et al (1973) found hardly any microbial growth on polystyrenes of molecular weight from 600 to 214,000 and on copolymers of styrene (comonomers included were: acrylic acid, sodium acrylate, dimethyl itaconate, acrylonitrile, ethyl acetate and methacrylonitrile). The chemical structure of polystyrene is basically similar to that of polyethylene (hydrogen atoms on alternate carbon atoms replaced by phenyl groups). The introduction of the phenyl groups does not render the polymer more bio-inert since aromatic rings themselves are biodegradable.

Thermal Effects

Short-term thermal changes can be particularly troublesome. During cold cycles, FML's are stretched tight in many locations in a lined facility. These same locations become very loose during warm cycles and (when uncovered) often lift off of the ground where a wavy surface is commonly seen to occur. Such variations even occur when cloud cover shields the sun from striking the FML surface. Table 7.2 gives the coefficient of thermal expansion of some common polymers and calculates the amount of deformation that occurs in section 1', 10' and 100' in length due to a temperature change from 100°F down to 50°F. Also shown is the equivalent tensile strain that is mobilized in these sections due to this contraction. While these equivalent strains appear low, they are calculated assuming that the strain will be uniform over the entire length of the FML. In the field this rarely occurs. Instead the strains tend to be very localized and can lead to significant fabrication problems and possible failure of seams.

Table 7.2 Thermal Properties of FML's and Illustration Showing the Influence of a Temperature Change of 50°F

Material	Average Coefficient of Thermal Expansion (x 10^{-5} per 1°F)	Change in Length (Deformation) for 1'	10'	100'	Corresponding Tensile Strain in FML (%)
Polyethylene					
low density	10	.0050	.0500	.500 ft.	.50
med. density	12.5	.0062	.0625	.6250	.62
high density	12.5	.0062	.0625	.6250	.62
Polypropylene	6.2	.0031	.0310	.3100	.31
Polyester, cast					
alloy type	4.2	.0021	.0210	.2100	.21
styrene type, rigid	4.8	.0024	.0240	.2400	.24
Polystyrene					
general purpose	4.0	.0020	.0200	.2000	.20
heat, chemical resistance	3.7	.0018	.0185	.1850	.18
Polyamide					
Nylon 6,6	5.5	.0028	.0275	.2750	.28
Nylon 6	5.0	.0025	.0250	.2500	.25
Nylon 11	5.5	.0028	.0275	.2750	.28

Temperature under natural conditions never reach the softening or melting point of the polymers. For example:

- Nylon 66: sticks at 445°F (229°C); melts at 500°F (260°C)
- Polypropylene: melts at 325°F (163°C) to 335°F (168°C),and
- Polyester: melts at 325°F (249°C to 550°F (288°C),

These temperatures cannot be reached unless some unnatural event occurs. Unfortunately, landfill fires are not at all uncommon and in such cases these high temperatures can be reached. They would be disastrous to the integrity of the FML.

The actual temperatures reached at the bottom and sides of a solid waste landfill have been measured and values as high as 160 °F have been reached. As shown in Table 7.3, Wolfgang (1959) gives a very comprehensive list of the burning characteristics of fibers. While not of direct concern to the FML itself, such elevated temperatures will actively promote biological growth which was discussed previously.

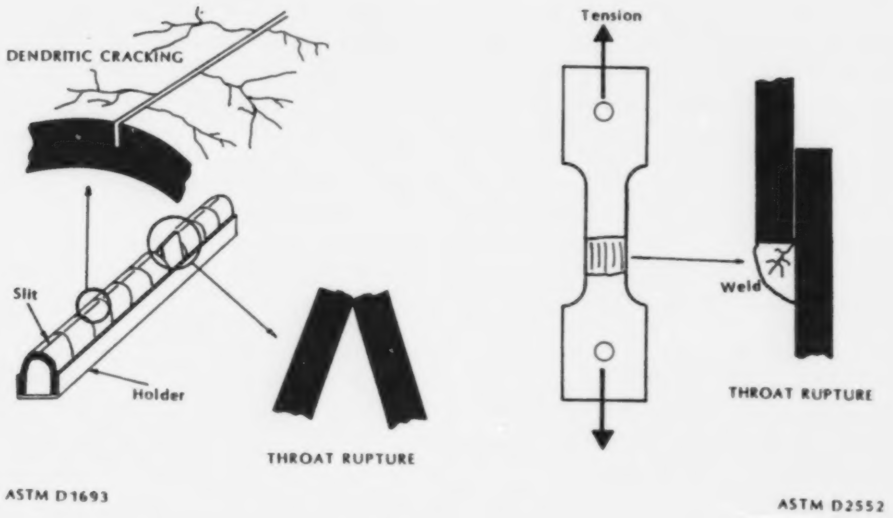
Table 7.3 Burning Characteristics of FML Polymeric Materials, after Wolfgang (1959)

Fiber	Polyethylene	Polypropylene	Polystyrene
Before touching flame	Melts, shrinks and curls from flame	Shrinks rapidly from flame, curls and melts	Melts, shrinks, and curls from flame
In flame	Melts and burns	Melts, ignites with difficulty	Melts and burns
After leaving	Burns rapidly	Burns slowly	Burns rapidly with production of great deal of soot
Odor	Burning paraffin	Faintly like burning asphalt	Benzene hyacinth
Ash	Soft, round same color as fiber	Hard, round light tan	Soft, round, same color as fiber

Environmental Stress Cracking

Stress cracking of polyethylene has been reported as early as 1950 by Carey (ASTM Bull, ASTBA, No. 167, July 1950), and its significance has been recognized via ASTM Standard D1693 entitled "Environmental Stress-Cracking of Ethylene Plastics". Under certain conditions of stress and in the presence of environments such as soaps, wetting agents, oils, detergents, or organic substances, ethylene plastics may exhibit mechanical failure by cracking. Figure 7.1a shows the existence of such cracking which occurred on laboratory test specimens but has also been similarly seen in field applications.

By definition, stress-crack is an external or internal rupture in a plastic caused by a tensile stress lower than the short term mechanical strength of the material. Failure is usually interpreted by visable



a. Environmental Stress Cracking b. Environmental Stress Rupture

Figure 7.1 Laboratory Environmental Stress Cracking/Rupture

evidence of cracks on the specimen's surface. The ASTM test requires a rectangular test specimen to be partially notched and then bent 180° and fitted into a specimen holder. The entire assembly containing a number of test specimens is placed in a borosilicate tube containing the test reagent. Thus the test is of the environmental stress cracking type. Unless stipulated otherwise, 48 hours is the immersion time after which the specimen holder is removed and the number of visual failures are recorded. Details of the test are presented in Appendix C.

It should be noted that environmental stress cracking is much less severe in FML's other than polyethylene. Quantitative details are, however, lacking in this area (as they are with most of the topics in this entire Section on long-term behavior problems).

Environmental Stress Rupture

Certain types of thermoplastic materials are sensitive to failure by cracking when exposed to surface active agents like detergents and organic substances. ASTM D2552 evaluates this sensitivity using constant stress (creep) tests on dogbone specimens immersed in the target liquid. The test is performed at a temperature of 50°C for a period of 168 hours. See Appendix C for details of the test setup. Three performance cases result from performing the test:

- elastic strains only
- plastic (ductile) strain giving rise to a noticeable degree of

deformation
- o brittle failure or fracture in a direction perpendicular to the direction of loading.

The distinction between the first two cases is the magnitude of the stress level verses the yield stress of the FML at 50°C. Stress levels less than yield will produce minor deformations while stress levels above yield leads to large deformations. The third case is of greatest concern and leads to cracking which is usually very dramatic and problematical.

All candidate FML polymers should be evaluated in this manner before final acceptance for use in a landfill or surface impoundment. Such tests should be carried out in both the FML sheet and the seams used to join sheeting. This latter case of seam cracking is quite possibly related to poor workmanship practices, see Figure 7.1b.

Aging Effects from Soil Burial

FML degradation due to burial in soil involves numerous chemical interactive processes. While very complex to assess, all involve the potential oxidation-reduction breaking of bonds, previously referred to as bond scission. Research involving soil burial is relatively scarce and certainly very fragmented. Some of the findings will be described here, but it should be noted that solid waste burial represents a much more aggressive environment than the reported work to date. As such, these findings should be considered "lower-bound" observations.

The ICI report cited earlier and reported in Rankilor (1981) presents numerous situations.

- o On Polyamides: Soil tests on 26 specimens were reported by Miner. Strength changes were the most noticeable for Nylon 6, where the following occurred:

  1 year burial - 90% of strength retained
  2 year burial - 90-88% of strength retained
  4 year burial - 80% of strength retained
  8 year burial - 75% of strength retained

  The loss of strength was attributed to polylmer degradation by hydrolysis due to soil moisture. Water is absorbed by the polymer and diffuses in it, thereby causing bond scission. These diffusion routes and their rates are quite important to assess and then to compare to the local environment (particularly when under elevated temperatures) and the level of mechanical stress.

- o On Polyester: Potts, et al report on caprolactone polyester exposed up to 12 months in an unidentified soil. The results were disasterous as seen in Table 7.4. While only conjecture, it is possible that the soil was highly alkaline, in which the above effects could have been anticipated. More complete details are given on this topic in the discussion of leachate collection/removal systems in this section.

Table 7.4 Soil Burial Tests on Polyester
after Potts,et al (1973)

Burial Time (months)	Tensile Strength (lb/sq.in.)	Elongation (%)	Weight Loss (%)
0	2610 + 103	369 + 59	0
2	1610 + 180	7 + 2.0	8
4	520 + 220	2.6 + 1.1	16
6	100	negligible	25
12	negligible	negligible	42

- On Polyolefins: For polyethylene and polypropylene buried up to 8 years, Miner (1973) found insignificant changes in strength. De Coste, however, found that high density polyethylene suffered major loss in elongation, even to the point of embrittlement, and a slight decrease in strength. This may not have been from the soil, however, since the air-aged specimens had similar results. Thus the results are not very conclusive.

- On Polyvinyl Chloride: The premier body of information on PVC liners is held by the U.S. Bureau of Reclamation. They have used PVC liners for water conveyance canals for over 20 years. Numerous reports have been issued on the subject of aging, see Morrison and Starbuck. In general, loss of plasticizer by leaching occurs over time resulting in black tacky surface deposits on the liner. This usually is accompanied by a slightly lower elongation at failure, higher tensile strength and higher modulus. There appears to be no direct evidence that the PVC resin itself has been degraded.

- On Polystyrene: Eight year soil exposure test were conducted by Miner (1972) who found a "mild effect" on these compounds. Details of the soil environment and the particular type of polystyrene were not included.

In all of the foregoing discussion, it must be remembered that this report deals with solid waste and "generic" families of plastic FML's. This latter point is worthwhile emphasizing since one type of polymeric liner material might (will) be very different than another. Haxo, et al (1984) gives a indication of the variations that a particular liner material can contain, Table 1.1. Notwithstanding the polymer variations, there are particularly hostile soils where care must be exercised.

- Acid sulphate soils occur in flat, swampy or marshy, organic areas and generate dilute surphuric acid . Solid waste is expected to produce similar conditions. The net effect is a very low pH where it is known, for example, that polyaramids deteriorate rapidly.

- Organic soils are troublesome in that three conditions usually result; organic acids and solvents are generated, water saturation occurs and microbial activity is high. Each situation is somewhat site-specific.

- Chemically active soils should obviously be dealt with cautiously. Usually grouped by pH and then followed by details such as the predominantly soluble salts or ferrous (ferric) oxide, the appropriate liner polymer is essentially handled via the chemical compatability testing protocol, e.g. EPA Method 9090.

- Volume-change soils such as result from expansive clays or frost heave are geotechnical engineering related phenomena and must be treated as such.

Echoing Rankilor's closing statement, "there is a clear indication of an increasing need for soil burial tests". We add, that when solid waste burial is involved the need is even greater.

LEACHATE COLLECTION/REMOVAL SYSTEMS

While some of this subsection has overlapped with the previous one, the emphasis here is on flow capability and clogging of drainage geosynthetics. Only those strength and elongation considerations which may affect the filtration and drainage functions will be considered, e.g. creep and stress relaxation. Discussion here centers on the geotextile filter placed under the solid waste and the geonet or geocomposite drains placed above the primary FML and between the primary and secondary FMLs.

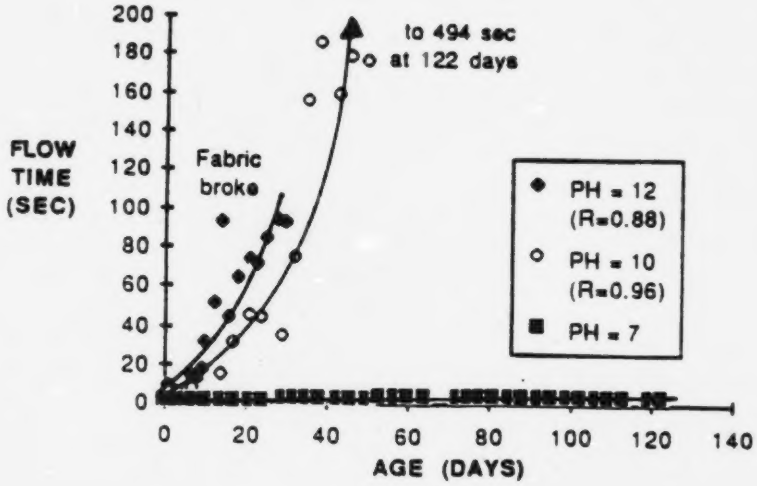
Creep/Stress Relaxation Effects

Both of these long-term influences have impact on the filtration and drainage capability of the geosynthetic systems involved. Creep is particularly important in both primary and secondary leachate collection and removal. At the extreme, of course, this flow capability can be completely cut off causing the system to fail. Creep designs were included in each of the designs of Section 3 where appropriate. The primary point to re-emphasize here is that a sufficiently high factor of safety on breakdown stress of the drainage core and strength of the geotextile is necessary. What this value is numerically, however, is a difficult decision unless specific experimental data is available. Some work has recently become available in this regard, e.g. see Slocumb, et al (1986).

Stress relaxation is relevant for the geotextile filter covering the primary leachate collection and removal system and for both primary and secondary FMLs on both sides of the secondary leachate collection and removal system. In both situations, large deformations can be anticipated (hence reduced drainage capability) unless high factors of safety on ultimate strength are used. Again conservatism is warranted in light of insufficient experimental data.

Chemical Attack

The chemical compatibility testing protocol for geotextiles, geonets and geocomposites is very poorly defined in contrast to FMLs. Standards organizations like ASTM are just beginning to become involved. While some form of strength is the usual focus for incubated FMLs (i.e. tensile, tear, puncture, etc.), one is at a loss to target a comparable property for geosynthetics used for a means other than a reinforcement function, i.e. for drainage. At this point in time it is probably best to use published values of polymeric chemical compatibility of which a sizeable list is available. Hoarz (1986) has recently published a large list from Amoco Chemicals Corp., Phillips Fibers Corp. and Hoechst Fibers Industries for both polypropylene and polyester. In such lists one sees trends, e.g., highly alkaline liquids degrade polyester geotextiles. However, to what degree and precisely when the pH is a factor is not mentioned. Table 7.5 by Kaswell (1963) gives some generalized comments. Needed is work which precisely defines the situation.



(Halse, et al)

Figure 7.2 Influence of pH on Permittivity of Geotextile

Figure 7.2 shows the time required for a constant quantity of alkaline water (of indicated pH) to flow through a 3 oz/sq. yd. polyester geotextile. Seen is that the time for a liquid of pH 7 liquid to flow was constant, however at pH 10 flow increased dramatically and at pH 12 the geotextile actually disintegrated. This response suggests that this type of polyester geotextile should simply not be used with any highly alkaline liquid. This information is currently under development for six commercially available geotextiles indicated in Table 7.6.

It should be noted that there is no known data set for geonet or geocomposite drainage systems currently available. It is of major concern and should be a high priority item.

Table 7.5 Chemical Resistance Properties of Fibers (Kaswell,1963)

	EFFECT OF ACIDS	EFFECTS OF ALKALIES	EFFECTS OF OTHER CHEMICALS	EFFECTS OF ORGANIC SOLVENTS	IDENTIFICATION
Nylon 6	Oxidizing agents and mineral acids such as hydrocloric and sulfuric cause degradation. Others such as bensoic and oxalic will cause loss in tenacity and elongation depending upon time and concentration.	Substantially inert.	Generally good resistance	Generally insoluble. Soluble in some phenolic compounds and in concentrated formic acid.	Melts before burning: self extinguishing. Insoluble in acetone or boiling NaOH solutions. Soluble in concentrated formic acid and xylol. Dissolves slowly in chloral hydrate.
Nylon 66	Boiling in 5% hydrochloric acid ultimately causes disintegration. Dissolves with at least partial decomposition in cold concentrated solutions of hydrocloric, sulfuric, and nitric acids.	Substantially inert.	Generally good resistance	Generally insoluble. Soluble in some phenoic compounds and in concentrated formic acid.	Melts before burning: self extinguishing. Insoluble in acetone or boiling NaOH solutions. Soluble in concentrated formic acid and xylol.
Darvan nytril	Little effect even at high concentrations.	Fair to good resistance to weak alkalies.	Generally good resistance	Generally insoluble	Calco identification stain #2 tints fiber grayish pink. At room temp., disolves in dimethyl formamide but insoluble in acetone
Polyethylene	Very resistant	Very resistant with the exception of oxidative agents.	Generally good resistance	Swollen at room temperature by chlorinated hydrocarbons, soluble at 160%F. Insoluble in aliphatic alcohols, glycerine, ether, carbon disulfide, and acetone.	Melts at 230-250 F°. Depending upon molecular weight. Floats in water. Insoluble in organic solvents at room temperature. Soluble in toluene, xylene, carbon tetrachloride at 160 ° F.
Polypropylene	Very resistant	Very resistant with the exception of oxidative agents.	Generally good resistance	Generally same as linear polyethylane.	Same as linear polyethylene except for higher melting point of 325-335 ° F.
Dacron polyester	Good resistance to most mineral acids. Dissolves with at least partial decomposition by concentrated solutions of sulfuric acids.	Good resistance to weak alkalies and moderate resistance to strong alkalies at room temperatures. Disintegrated by strong alkalies at boiling temperatures.	Generally good resistance. Excellent resistance to bleaches and other oxidizing agents.	Generally insoluble. Soluble in some phenolic compounds.	Melts before burning. Soluble in hot metacresol, but not soluble in acetone or concentrated formic acid.
Fortrel polyester	Good resistance to most mineral acids. Dissolves with at least partial decomposition by concentrated solutions of sulfuric acids.	Good resistance to weak alkalies and moderate resistance to strong alkalies at room temperatures. Disintegrated by strong alkalies at boiling temperatures.	Generally good resistance. Excellent resistance to bleaches and other oxidizing agents.	Generally insoluble. Soluble in some phenolic compounds.	Melts before burning. Soluble in hot metacresol, but not soluble in acetone or concentrated formic acid.
Kodel polyester	Good resistance to most mineral acids, and fair resistance to concentrated sulfuric acid.	Good resistance to most alkali concentrations at room temperature. Disintegrated by strong alkalies at the boil.	Not affected by most common chemicals. Good resistance to bleaches and other oxidizing agents.	Not affected by most commercial solvents.	Melts before burning. Insoluble in acetone, hydrochloric acid, sodium hypochlorite and methylene chloride. Slightly soluble in 70% sulfuric acid and in 45% sodium hydroxide. Distinguishable from other polyesters by insolubility in a mixture of one hydrazine and 9 parts butyl alcohol.
Vyeron	Good resistance to most mineral acids. Dissolves slowly in concentrate sulfuric and formic acids.	Good resistance to weak alkalies and to moderate concentrated alkalies at room temperature. Decomposes in strong hot alkalies.	Generally unaffected by most common chemicals.	Unaffected by most solvents.	Distinguishable from other polyesters by characteristic infrared spectrum and X-ray distraction patterns.

Table 7.6 Akalinity Study on Geotextiles of the Type Shown in Fig. 7.4

No.	Polymer	Fabric Construction	Mass/Unit Area
1	Polypropylene (PP)	Woven monofilament	2.9 oz/sq.yd.
2	Polyvinylchloride (PVC)	Woven monofilament	2.8
3	Polyester (PET)	Needle non-woven	14.7
4	Polypropylene (PP)	Needle non-woven	19.5
5	Polyester (PET)	Heat set non-woven	3.0
6	Polypropylene (PP)	Heat set non-woven	3.0

Biological (Micro-organism) Attack

It is almost certain that micro-organism growth of bacteria and fungi will affect the filtration capability of geotextiles and the drainage capability of geonets and geocomposites. The initial phenomenon is clearly one of blocking and/or clogging rather than degradation as was the case with FMLs. It is also possible that the attachment of the micro-organisms onto the geosynthetic will cause long-term degradation, but this has not been documented. What work is available in the literature concerns geotextiles. Ionescu, et al. (1982) tested six types of geotextiles consisting of different mechanical and hydraulic properties. They were as follows;

- needled nonwoven polypropylene (fine, short staple fibers)
- needled nonwoven polypropylene (coarse, long staple fibers)
- needled and resin bonded nonwoven polyester (fine, short staple fibers
- needled and resin bonded mixed polymer (various fine, short staple fibers
- woven polypropylene, from fribrillated yarns
- woven polypropylene, fibrillated in warp

The incubation media included the following:

- distilled water (control medium)
- iron bacteria of pH = 6.5
- desulfovibrios medium of pH = 7.0
- levan-synthesizing bacteria of pH = 7.0
- liquid mineral medium of pH = 7.0
- water collected from the Black Sea.
- compost from plant residues
- fertile alluvial soil

They found some micro-organism growth in the iron bacteria, desulfovibrious and leva-synthesizing bacteria, but in insufficient amounts to affect the filtration capability of the geotextiles. Tensile strength of the geotextiles remained unchanged and infrared spectrograms showed that no fiber degradation had occurred. Thus the biological growth problem in geotextiles was not a major issue according to Ionescu, et al (at least within the limits of their study).

More recently, however, Troost and den Hoedt (1985) found otherwise. For the following cultures, under under 13 months of exposure, severe strength reductions did indeed occur;

- Alternaria alternata
- Aspergillus versicolor en niger
- Chaetomium globosum
- Cladosporium herbarum en species
- Fusarium species
- Paecilomyces variotti
- Penicillium expansum
- Stachybotrys atra
- Ulocladium chartarum

The resulting data shown on Table 7.7 is for six commercially available geotextiles. As micrographs clearly indicated, both rapid growth on the fibers and weakening of them did indeed occur.

This contrasting set of data (Ionescu, et.al. vs. Troost/den Hoedt) is indicative of the lack of a adequate data base from which any degree of confidence can be gained. Furthermore, it should be understood that the drainage situation in geonets and geocomposites has not been addressed at all, nor have elevated temperatures acting over long time periods.

Table 7.7 Biological Effects on Geotextile Strength, after Troost and den Hoedt (1985)

No.	Polymer	Initial Strength kN/m	Weight g/m2	% Residual Strength After 3 mos.	13 mos.
A	PP	30	220	75	75
B	PE	45	180	91	90
C	PA	75	230	99	99
D	PES	65	230	98	97
E	PES	200	450	100	99
F	PP	200	730	76	75

Thermal Effects

Two subjects must clearly be separated in tabulating the influence of heat upon fiber properties: (1) tensile properties of fibers tested at elevated temperatures; and (2) tensile properties of fibers tested at room temperature after exposure to elevated temperatures for selected time periods. The former indicates the capability of the fiber to perform at the required elevated temperature. The latter is often used as a criterion of heat degradation resistance. Both effects for various fibers from which geotextiles are made are listed in Table 7.8. Completely lacking in the literature are thermal effects on the performance of geonets and geocomposites.

Aging Effects from Soil Burial

General aging effects on the performance geotextiles, geogrids and geocomposites buried in solid waste is completely unknown. While obviously a combination of chemical, biological and thermal mechanisms can occur there are a host of open ended questions. Indeed the potential synergism between these different phenomena while the material is in service and under stress is a further complication.

Some insight can be gained, however, by assessing the effects of soil burial where a few long-term studies with geotextiles have been reported. Sotton, et al. (1982) examined samples which were in place for up to 12 years. Both mechanical and hydraulic properties were examined and compared to original properties. Losses were generally nonimal with maximum losses of 30%.

The National Research Council of Canada (Koerner, 1986) is testing the effects of burial on fabrics. Recognizing that soil is very variable material, their test soils range from 99% organic to 100% inorganic, have a wide range of pH values, and vary greatly in elemental composition and microorganism content. The tests involve 12 cm x 12 cm fabric samples of polyethylene terephthalate, polypropylene, and nylon-polypropylene biocomponent fabrics. The test method is designated CGSB 4-GP-2 Method 28.3 and is similar to AATCC Test Method 30-1974 and Federal Standard No. 191, Method 5762. Samples are removed at 3-month intervals and are tested according to the diaphragm pressure (Mullen burst) test found in ASTM Method D774. Future testing will involve other fabrics and a wider range of soil conditions.

The Proceedings of the 3rd International Conference on Geotextiles in Vienna (1986) produced several papers of interest in this regard. For example, Metei, et al (1986) show results for geotextiles in place up to 5 years with minor change in properties, see Table 7.9. By far, the most important development to date in this area of soil degradation of geotextiles has been the November 4-6, 1986 Seminar by RILEM entitled "Long Term Behavior of Geotextiles" in France. The Proceedings of this Seminar are unavailable at the time of this writing.

CELL CAP PERFORMANCE

Concern for the FMC's along with their associated surface water collection and removal systems have many long-term features in common with the FML's and leachate collection and removal systems beneath the waste. Thus the sections on biological, thermal, stress cracking and aging effects are completely applicable here as well as in Sections 7.1 and 7.2. There are, however, a few differences which warrant this special section.

Hydrolysis Effects

While undoubtedly more subtle than chemical effects due to leachate exposure, polymeric materials exposed to water (rainfall and snowmelt) will react over long time periods. Moisture adsorption and imbibition are well known phenomena and average values are well documented, see Table 7.10.

Table 7.8 Effect of Heat on Fiber Properties, after Kaswell, 1963

Fiber	Effect of Heat Exposure on Properties	Physical Properties at Elevated Temperature
Nylon 6 (regular)	Sticking temperature - 400°F Melts at 420°-430°F. Slight discoloration at 300°F for 5 hours. Decomposes at 600°F.	Tenacity decreases with temperature increase. Shrinks when heated.
Nylon 11	Melting point 365°F.	
Nylon 66 (regular)	Sticking temperature 455°F Melts at 482°F.; turns slightly yellow when heated in air at 300°F. for 5 hours.	70°F 5.0 gm/den 28% elong 200°F 4.7 gm/den 27% elong 300°F 3.3 gm/den 32% elong
Polyethylene low density	Softens at 225-235°F; melts at 230-250°F. Thermally sensitive with respect to shrinkage.	--
Polyethylene high density	Softens at 240-250°F; melts at 255-280°F.	--
Polypropylene	Softens at 300-310°F.; melts at 325-335°F.	--
Polyvinyl alcohol	Yellows slightly at 428°F.; melts above 430°F.	--
Dacron polyester	Sticking temperature 455°F; no color change 7 days at 302°F. Melts at 480°F; safe ironing temperatures up to 360°F. if fabric has been stabilized.	70°F 5.0 gm.den 17% elong 176°F 4.2 gm/den 30% elong 348°F 3.6 gm/den 38% elong 320°F 3.0gm.den 45% elong
Fortrel polyester	Melts at 482°F.	
Kodel polyester	Melts at 555°F.; safe ironing temperature below 425°F.	70°F. 2.5-3.0 gm/den
Vycron polyester	Melts at 450°F.	

These values, however, do not indicate the extent of the interactions. One needs the actual behavior, as shown in Figure 7.3 for nylon 66 and dacron polyester, in order to get a clear perspective of the influence under load. Needed, of course, is the long-term behavior for assessment of the cell cap performance.

Table 7.9 Results of Soil Burial Tests, after Matei, et al (1986)

Geotextile	Time in operation (years)	Characteristics: Breaking force (kN/5 cm)	Elongation at failure (%)	Coefficient of normal permeability K(m/s)
Madril M 400	0	0.68	88	0.60x10-3
	2	0.43	69	0.58x10-3
Terram 1000	0	0.47	44	0.30x10-3
	3	0.36	34	--
	5	0.45	33	0.13x10-3
Drenadex	0	0.95	44	3.00x10-3
	5	0.97	45	1.80x10-3

Gas Venting and Interaction

As described in detail in Section 4, gases are indeed generated in solid waste facilities in varying amounts and over varying periods of time. Figure 7.4 gives a qualitative indication of the situation. Here it is seen that both methane and carbon dioxide are produced in the greatest amount but also many other gases are generated in lesser quantities. The major polymeric materials in the cell cap that these gases interact with are the gas collection geotextile and the underside of the secondary FMC. There are no known test methods nor references on this topic although the literature on filtration of industrial and stack gases is very abundant. Technology transfer from this area is warranted.

Special Concerns

There are a series of special concerns for cell cap performance over long periods of time which almost defy a quantitative analysis. Instead they require sound judgment and a realistic (and futuristic) assessment of possible harmful events. The group which has had some experience in such an assessment is various Deparment of Energy contractors who have a mandate to cover low-level radioactive waste sites. Here time frames are every bit as long as with hazardous materials, and perhaps even longer. This section is written with long-term concerns in mind.

Root Penetration --

Plant and tree roots can penetrate very deep into the subsoil. The depth is obviously dependent upon the type of plant, type of soil, geographic location, etc, but depths of many feet are not uncommon. To be sure, the depth of soil cover over a geosynthetic cap (4.0 ft) is within reach of many plants under a wide variety of conditions. At the minimum,

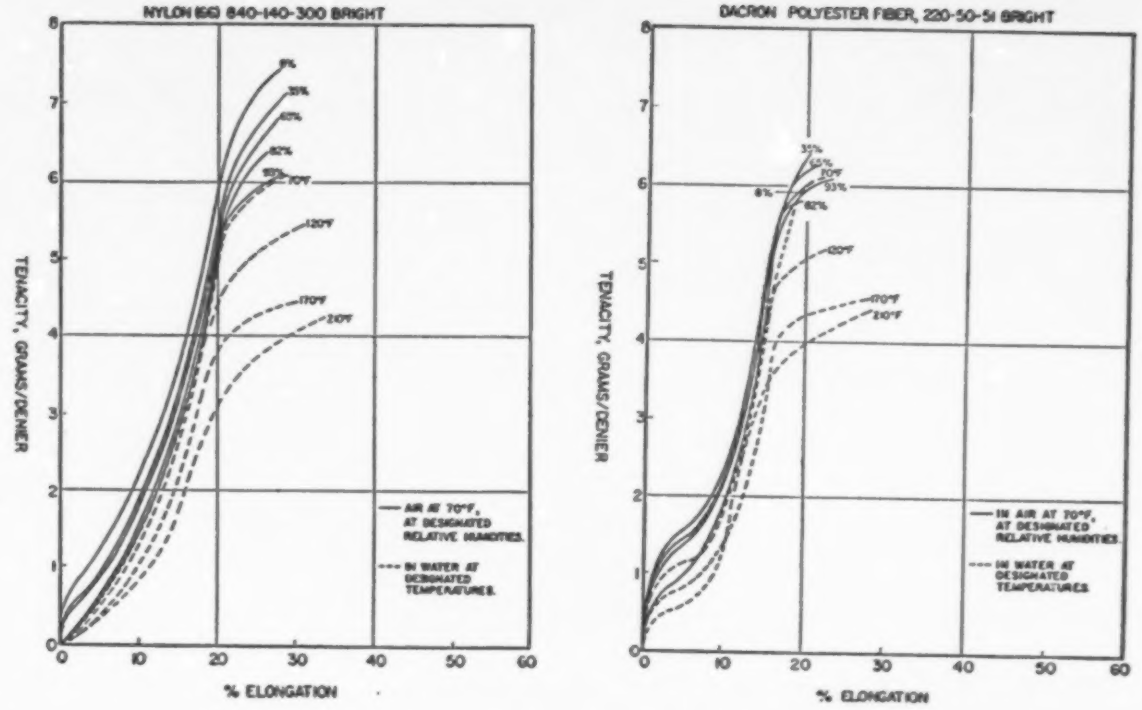


Figure 7.3 Strength Behavior of Nylon and Polyester in Water

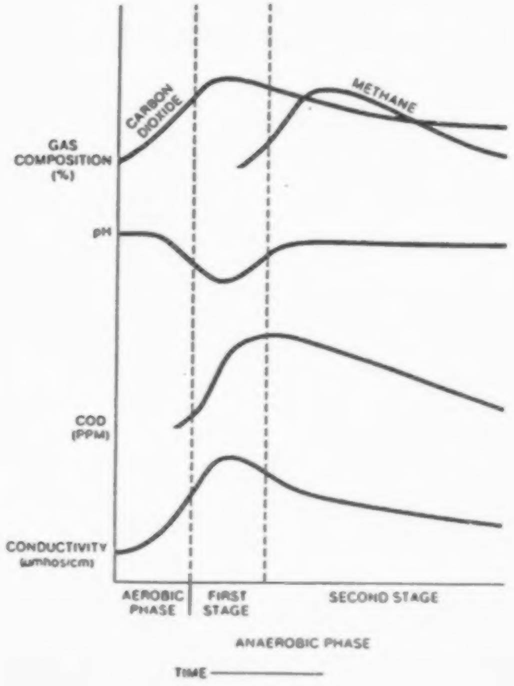


Figure 7.4 Phases of Solid Waste Decomposition

Table 7.10 Moisture Regain and Water Imbibition of Fibers, after Kaswell, 1963

	Percent Moisture Regain at		Percent Water Imbibition(Q)
	70°F., 65% R.H.	70°F., 95% R.H.	
Nylon 6, regular	4-5	6.5-8.5	--
Nylon 6, high tenacity	4-5	6.5-8.5	--
Nylon 66, regular	4.5	8.0	10
Nylon 66, high tenacity	4.5	8.0	--
Nylon 11	1.18	--	--
Polyethylene, low density	0	less than 0.1	0.01
Polyethylene, high density	0	less than 0.1	0.01
Polypropylene	0	0	--
Polyvinyl alcohol	4.5	--	25-35
Dacron polyester, regular	0.45-0.8	0.5	0.9
Dacron polyester, high tenacity	0.4-0.8	0.5	2.0
Fortrel polyester	0.4	--	--
Kodel polyester	0.4	0.8	--
Vycron polyester	0.6	--	2.0

one could anticipate the roots to penetrate the geotextile filter, work themselves into the geocomposite drainage core space and eventually partially, or completely, block the surface water collection and removal system. The ways to stop such a situation would be to design a very deep soil cover layer or to select vegetative growth which does not contain deep root systems. While this second alternate is the obvious choice, one can easily visualize many years after closure where vegetation develops from natural circumstances and create severe damage. The situation is one, however, where remedial action can be taken without disturbing the FMC.

Burrowing Animals --
Rodents and other burrowing animals present a severe challenge to the long-term life of a cell cap closure. While going for a food source they will penetrate through almost anything, certainly through a synthetic liner system. The muskrat problem in Dutch river dikes is a notorious and well known situation. The key here seems to be lack of moisture. If the primary surface water collection system properly drains its water (rapidly and completely), there should be no compelling reason for animals to burrow through the closure into the encapsulated solid waste. Thus localized depressions, i.e., bathtubs, must be avoided. Other concepts, such as layer of heavy gravel or cobbles within the soil cover have been considered for low level radioactive cover systems and may be applicable to hazardous waste landfills as well.

Wind Erosion --
Wind erosion is a well known and definable process which should be within the design state-of-the-art. It is very much a site specific situation, but one in which reasonable design assurity should be

attainable. For high above-ground landfills the shape and general configuration of the surrounding area must be considered. For situations of particular concern, wind tunnel studies to evaluate the aerodynamics of the final configurations are not beyond reason.

Water Erosion --

As with the previously discussed wind erosion, the problem of water erosion is also site-specific. This subject, too, has been evaluated and designs are available. Geosynthetics play an important role in this area for many erosion-control systems are available which use mats, webbings, nets, lattices, threads, etc., made from polymeric materials. The mechanisms that they function under are to allow for growth to establish itself and simultaneously retard erosion, see Koerner (1986) for a number of these systems. Their lifetimes are not of critical concern for their main mission is to promote natural vegetative growth to resist potential erosion. If this growth should subsequently die, then the lifetime of the synthetic erosion control system would be an issue.

Man-Made Intrusion --

Here is perhaps the most dangerous of these special concerns; Love Canal bears testimony to this statement. Proper signs, fences, warnings, etc., seem destined to short-term lives. Focus for the long term must be on the closed solid waste facility itself. Its size, shape and presence must itself engender caution or danger to a potential intruder. Further note that this intrusion may be accidental or intentional. The intentional situation is of maximum concern. Considerable care and concern are certainly warranted on this issue, as are all of the issues in this section on Special Concerns.

Asthetics --

To date, completed landfill caps are ominous zones buffered from the public by fencing. The effect to the region is much like that obtained by munitions dumps; vast open areas that appear to be permanently lost for public use. Recently some public landfill owners have begun to explore alternatives for such cultural dead zones. An example of this is the recent commissioning of artist Nancy Holt by the Hackensack Meadows Development Commission to transform a municipal waste landfill cap into an environmental art form. The 57 acre cap will be transformed into a "Sky Mound" that includes earth mounds up to 100 feet in height. These mounds will frame sunrises and sunsets when viewed from the center of the cap. The astronomy theme is carried on to an interior lunar zone that is surrounded by a circular moat that serves as part of the surface water collection system and looping arches of the methane recovery system. Pipe tunnels through selected mounds are aligned with stellar helical settings of the stars Sirius and Vega. These extrordinary features are shown on Figure 7.5. Land surrounding the cap will be converted to a wild bird refuge.

While not endorsing the specifics of the Hackensack project, it is clear that the cultural impact of a landfill cap can be minimized. However it should be cautioned that features such as earth mounds or surface impoundments within the cap must be carefully engineered to prevent damage to the underlying cap system. Differential settlements that are the result of surcharges generated by mounds or other 'art' features could easily lead to failure of the FMC. The longterm performance of the cap must not be compromised by surface structures regardless of their function or intent.

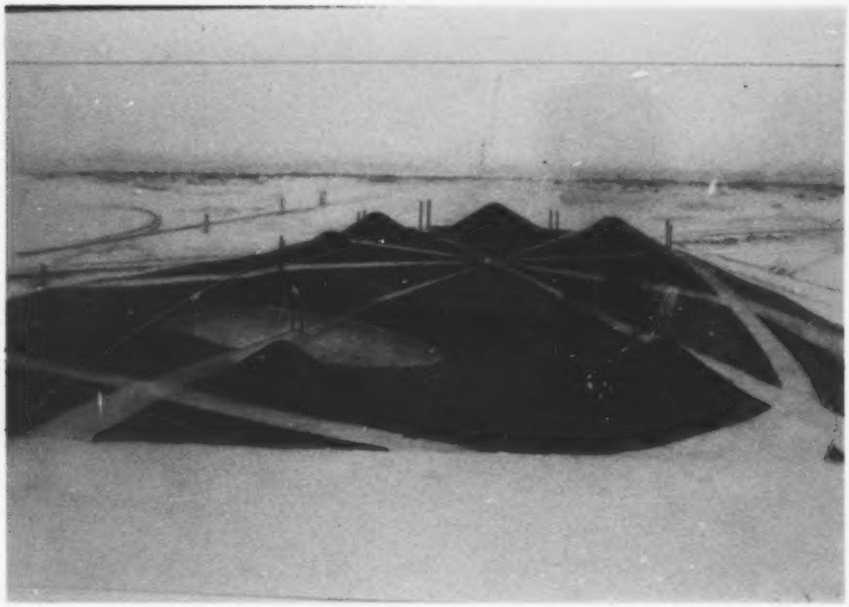


Figure 7.5 "Sky Mound" Cap Planned for Hackensack Meadowland

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Appendix A Conversion of Units

LENGTH

1 mm = 0.0394 in.
1 cm = 10 mm = 0.394 in.
1 m = 100 cm = 39.4 in. = 3.28 ft.
1 km = 1000 m = 3280 ft. = 0.621 mile
1 in. = 2.54 cm
1 ft. = 0.305 m
1 yd. = 0.914 m
1 mile = 1.609 km

CAPACITY

1 liter = 1000 cm^3
1 liter = 61.0 in.^{3}
1 liter = 0.264 U.S. gallon
1 U.S. gallon = 3785 cm^3
1 U.S. gallon = 231 in.^{3}
1 U.S. gallon = 3.78 liters
1 cm^3 = 0.001 liter
= 2.64×10^{-4} U.S. gallon
1 ft^3 = 7.48 U.S. gallon = 28.3 liters

UNIT WEIGHT

1 N/m^3 = 1.02×10^{-4} g/cm^3
= 6.37×10^{-3} lb/ft^3
1 g/cm^3 = 9.81×10^3 N/m^3
= 62.4 lb/ft^3
1 lb/ft^3 = 1.57×10^2 N/m^3
= 1.60×10^{-2} g/cm^3

AREA

1 cm^2 = 0.155 in.^{2}
1 m^2 = 10.8 ft^2 = 1.20 yd^2
1 ha = 2.47 acres
1 in.^{2} = 6.45 cm^2
1 ft^2 = 0.0929 cm^2
1 yd^2 = 0.835 m^2
1 acre = 0.405 ha
= 43,560 ft^2

VOLUME

1 cm^3 = 0.0610 in.^{3}
1 m^3 = 35.3 ft^3 = 1.31 yd^3
1 in.^{3} = 16.4 cm^3
1 ft^3 = 0.0283 m^3
1 yd^3 = 0.764 m^3

TEMPERATURE

1°C = 1°K = 1.8°F
1°F = 0.555°C = 0.555 K
0 K = −273°C = −460°F
$T_c = (5/9)(T_f - 32^\circ)$
$= T_k - 273^\circ$
$T_k = T_c + 273^\circ$
$= (T_f + 460)/1.8$
$T_f = (9/5)T_c + 32^\circ$
$= 1.8T_k - 460^\circ$

STRESS

1 N/m^2 = 1 Pa
= 1.02×10^{-5} kg/cm^2 = 1.45×10^{-4} lb/in^2
= 2.08×10^{-2} lb/ft^2 = 1.04×10^{-5} ton/ft
1 kg/cm^2 = 9.81×10^4 N/m^2 = 14.2 lb/in^2 = 2.05×10^3 lb/ft^2
= 1.02 tons/ft^2
1 lb/in.^{2} = 6.89×10^3 N/m^2 = 7.03×10^{-2} kg/cm^2 = 144 lb/ft^2
= 7.2×10^{-2} ton/ft^2
1 lb/ft^2 = 4.79×10 N/m^2 = 4.88×10^{-4} kg/cm^2
= 6.94×10^{-3} lb/in.^{2} = 5.00×10^{-4} ton/ft^2
1 ton/ft^2 = 9.58×10^4 N/m^2 = 9.76×10^{-1} kg/cm^2
= 13.9 lb/in.^{2} = 2000 lb/ft^2

FORCE

1 N = 102.0 g = 0.225 lb = 1.124×10^{-4} ton
1 g = 9.81×10^{-3} N = 2.20×10^{-3} lb = 1.102×10^{-6} ton
1 lb = 4.45 N = 453.6 g = 5.00×10^{-4} ton
1 ton = 8.89×10^3 N = 9.07×10^5 g = 2000 lb

Appendix B GLOSSARY

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abrasion,
the ability of a fabric to resist wear caused by rubbing against another surface.

abrasion resistance,
the ability of fabric surface to resist wear by friction.

absorption,
for geotextiles, the process of a fluid being assimilated or incorporated into a fabric.

actinic degradation,
strength loss of fibers and fabrics due to exposure to sunlight or accelerated weathering light source.

adhesion,
the state in which two surfaces are held together by interfacial forces which may consist of molecular forces or interlocking action or both. Measured in shear and peel modes.

air lance,
a device used to test, in the field, the integrity of field seams in plastic sheeting. It consists of a wand or tube through which compressed air is blown.

alloys, polymeric,
a blend of two or more polymers (e.g., a rubber and a plastic) to improve a given property (e.g., impact strength).

anchor trench,
a long, narrow ditch on which the edges of a plastic sheet are buried to hold it in place or to anchor the sheet.

apparent opening size (AOS),
see equivalent opening size (EOS)

arching,
the formation of soil particles upstream of a geotextile where the particles arch (or bridge) over the fabrics' voids.

area change,
increase or decrease in the area of fabric specimen subjected to a specified condition.

aspect ratio,
the width to length ratio of a fabric test specimen prior to uniaxial tensile testing.

atmosphere for testing geotextiles,
for geotextiles, air maintained at a relative humidity of 65 ±5% and a temperature of 21 ±2°C.

basis weight,
deprecated term (do not use in the sense of mass per unit area).

berm,
the upper edge of a pit or pond where a membrane liner is anchored. The berm may be wide and solid enough for vehicular traffic.

biaxial tensile test,
a tensile test in which a fabric specimen is subjected to tensile forces in two directions 90° to one another, usually the machine and cross-machine directions.

biological stability,
ability to resist degradation from exposure to microorganisms.

blinding,
the condition where soil particles block openings on the surface of a geotextile, thereby reducing hydraulic conductivity of the geotextile.

blocking,
a synonymous term for blinding or also when sheets of am FML stick together due to excessive heat and pressure.

blocking,
a synonymous term for blinding.

bodied solvent adhesive,
an adhesive consisting of a solution of the liner compound used in the seaming of liner membranes.

bonding,
the process of combining fibers, filaments, or films into sheets, webs or bats by means of mechanical, thermal, or chemical binding.

boot,
a bellows-type covering to exclude dust, dirt, moisture, etc., from a flexible joint.

breaking factor,
tensile at break in force per unit of width: units, SI, newtons per meter; customary, pounds per inch.

burst strength,
the resistance of a fabric to rupture from pressure applied at right angles to the plane of the fabric under specified conditions, usually expressed as the pressure causing failure. Burst result from tensile failure of the fabric.

butyl rubber,
a synthetic rubber based on isobutylene and a minor amount of isoprene. It is vulcanizable and features low permeability to gases and water vapor and good resistance to aging, chemicals, and weathering.

calender,
a precision machine equipped with three or more heavy internally heated or cooled rolls, revolving in opposite directions. Used for preparation of highly accurate continuous sheeting or plying up of rubber compounds and frictioning or coating of fabric with rubber or plastic compounds.

chemical bonding,
a bonding process in which the individual fibners in the fabric web are cemented together by chenmical interaction.

chemical stability,
ability to resist chemicals, such as acids, bases, solvents, oils and oxidation agents; and chemical reactions, including those catalyzed by light.

chlorinated polyethylene (CPE),
family of polymers produced by chemical reaction of chlorine on the linear backbone chain of polyethylene. The resultant rubbery thermoplastic elastomers presently contain 25 to 45% chlorine by weight and 0 to 25% crystallinity. CPE can be vulcanized but is usually used in a nonvulcanized form.

chlorosulfonated polyethelene (CSPE)
family of polymers that are produced by polyethelene reacting with chlorine and sulfur dioxide. Present polymers contain 25 to 43% chlorine and 1.0 ro 1.4% sulfur. They are used in both vulcanized and nonvulcanized forms. Most membranes based on CSPE are nonvulcanized (ASTM designation for this polymer is CSM).

clogging,
movement by mechanical action or hydraulic flow of soil particles into the voids of fabric and retention therein, thereby reducing the hydraulic conductivity of the geotextile.

coated fabric,
fabric which has been impregnated and/or coated with a rubbery or plastic material in the form of a solution, dispersion, hot melt, or powder. The term also applies to materials resulting from the application of a preformed film to a fabric by means of calendering.

composite,
See Fabric, composite.

compressibility,
property of a fabric describing the ease with which it can be compressed normal to the plane of the fabric.

constant-rate-of-extension tensile testing machine (CRE),
a testing machine in which the rate of increase of specimen length is uniform with time.

constant-rate-of-load tensile testing machine (CRL),
a testing machine in which the rate of increase of the load being applied to the specimen is uniform with time.

constant-rate-of-traverse tensile testing machine (CRT),
a testing machine in which the pulling clamp moves at a uniform rate and the load is applied through the other clamp which moves appreciably to actuate a weighing mechanism, so that the rate of increase of loads or elongation is dependent upon the extension characteristics of the specimen.

creep,
the slow change in length or thickness of a material under prolonged stress.

creep (static),
increasing strain at constant stress.

cross-linking,
a general term referring to the formation of chemical bonds between polymeric chains to yield an insoluble, three-dimensional polymeric structure. Cross-linking of rubbers is vulcanization. See also Vuncanization.

cross-machine direction,
the axis within the plane of a fabric perpendicular to the machine direction.

cross plane,
the direction of a geosynthetic which is perpendicular to its long, manufactured, or machine direction. Referred to in hydraulic conductivity of a geotextile.

curing,
See Vulcanization.

cutting resistance,
the resistance of the fabric or fiber to cutting when struck between two hard objects.

deformation,
the lengthening of a geosynthetic under load from its original manufactured dimensions.

denier,
the weight in grams of 9000 m of yarn.

density,p,
mass per unit volume.

dielectric seaming,
See Heat seaming.

dimensional change,
a generic term for changes in length or width of a fabric specimen subjected to a specified condition.

direction, cross machine,
in textiles, the direction in a machine-made fabric perpendicular to a direction of movement the fabric followed in the manufacturing machine (syn. widthwise).

direction, machine,
in textiles, the direction in a machine-made fabric parallel to the direction of movement the fabric followed in the manufacturing machine (syn. lengthwise).

downstream,
the direction on the opposite side of a geotextile from which water is moving.

elasticity,
the property of matter by virtue of which it tends to return to its original size and shape after removal of the stress which caused the deformation.

elastomer,
See Rubber.

elongation,
the increase in length produced in the gage length of the test specimen by a tensile load.

elongation at break, E_B,
the percent elongation corresponding to the breaking strength, that is, the maximum load.

elongation, percent, E,
for geotextiles, the increase in length of a specimen expressed as a percentage of the nominal gage length.

EPDM,
a synthetic elastomer based on ethylene, propylene, and a small amount of a nonconjugated diene to provide sites for vulcanization. EPDM features excellent hear, ozone, and weathering resistance and low-temperature flexibility.

epichlorohydrin rubber,
this synthetic rubber includes two epichlorohydrin-based elastomers which are saturated, high-molecular-weight, aliphatic polyethers with chloromethyl side chains. The two types include a homopolymer (CO) and a co-polymer of epichlorohydrin and ethylene oxide (ECO). These rubbers are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group, including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

epoxy binding,
a bonding process in which the fabric web is impregnated with epoxy which serves to coat and cement the fibers together.

equivalent opening size (EOS),
number of the U.S. Bureau of Standard sieve (or its opening size in millimeters or inches) having openings closest in size to the diameter of uniform particles which will allow 5% by weight to pass through the fabric when shaken in a prescribed manner.

EVA,
family of co-polymers of ethylene and vinyl acetate used for adhesives and thermoplastics modifiers. They possess a wide range of melt indexes.

extruder,
a machine with a driven screw for continuous forming of rubber by forcing through a die; can be used to manufacture films and sheeting.

fabric, composite,
a textile structure produced by combining non-woven, woven, or both manufacturing methods.

fabric, knitted,
a textile structure produced by interlooping one or more ends of yarn or comparable material.

fabric, non-woven,
for geotextiles, a planar textile structure produced by bonding, interlocking of fibers, or both, accomplished by mechanical, chemical, thermal, or solvent means, and combinations thereof. NOTE: The term does not include paper or fabrics which are woven, knitted, or tufted.

fabric, woven,
a planar textile structure produced by interlacing two or more sets of elements such as yarns, fibers, rovings or filaments where the elements pass each other usually at right angles and one set of elements are parallel to the fabric axis. NOTE: Excluded are knotted fabrics.

fabric reinforcement,
a fabric, scrim, and so on, used to add structural strength to a two- or more ply polymeric sheet. Such sheeting is referred to as "supported."

fatigue resistance,
the ability to withstand stress repetitions without suffering a loss in strength.

felt,
a sheet of matted fibers made by a combination of mechanical and chemical action, pressure, moisture, and heat.

fiber,
basic element of fabrics and other textile structures, characterized by having a length at least 100 times its diameter or width which can be spun into a yarn or otherwise made into a fabric.

filament,
a fiber of extreme length.

filament yarn,
the yarn made from continuous filament fibers.

fill,
fibers or yarns placed at right angles to the warp or machine direction.

filling,
yarn running from selvage to selvage at right angles to the warp in a woven fabric.

filling direction,
see direction, cross machine. NOTE: For use with woven fabrics only.

film,
sheeting having nominal thickness not greater than 10 mils.

filter cake,
a thin layer of fine soil particles accumulated in the soil adjacent to the fabric as a result of smaller soil particles being washed through the soil pores.

filter cloth,
the depracated term for geotextile.

filtration,
the process of allowing water to easily escape from soil while retaining soil in place.

flexural rigidity,
general: resistance to bending or flexural rigidity is called flex stiffness in Federal Specification CCC-T-19 lb., Textile Test Methods No. 2506.2.
specific: , the couple on either end of a strip of unit width bent into curvature in the absence of tension. The method measures the bending length. Flexural rigidity is calculated directly by multiplying the cube of the bending length by the weight per unit area.

freez-thaw resistance,
ability to resist degradation caused by freeze-thaw cycles.

friction angle,
an angle, the tangent of which is equal to the ratio of the friction force per unit area to the normal stress between two materials.

geocell,
a three-dimensional structure filled with soil, thereby forming a mattress for increased bearing capacity and maneuverability on loose or compressible subsoils.

geocomposite,
a manufactured material using geotextiles, geogrids, and/or geomembranes in laminated or composite form.

geogrid,
a deformed or nondeformed net like polymeric material used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of human-made project, structure, or system.

geomembrane,
an essentially impermeable membrane used with foundation, soil, rock, earth or any other geotechnical engineering related material as an integral part of a man-made project, structure, or system.

geosynthetics,
the generic classification of all synthetic materials used in geotechnical engineering applications; it includes geotextiles, geocells, geogrids, geomembranes, and geocomposites.

geotechnical engineering,
the engineering application of geotechnics.

geotechnics,
the generic classification of all synthetic materials used in geotechnical engineering application; it includes geotextiles, geocells, geogrids, geomembranes, and geocomposites.

geotechnology,
the application of science and engineering techniques to the exploitation and use of natural resources such as mineral resources.

geotextile,
any permeable textile used with foundation, soil, rock, earth, or any other geotechnical engineering related material as an integral part of a man-made project, structure, or system.

geotextile tensile modulus, J,
the ratio of the change in tensile force per unit width of the geotextile to the change in corresponding strain. The geotextile modulus is usually expressed in N/m (lbf/in).

geotextile tensile modulus, initial, J.,
for geotextiles, the slope of the initial portion of a force per unit width curve. Discussion: The initial modulus is the ratio of the change in force to the change in elongation. The elongation being expressed as a fraction of the original length.

geotextile tensile modulus, secant, Jsec,
the ratio of change in force per unit width to a change in elongation between two points on a force per unit width curve, particularly the points of zero force and a specified percent elongation. Discussion: The secant is expressed as a fraction of the original length.

grab tensile strength,
a modified tensile strength of a fabric. The strength of a specific width of fabric together with the additional strength contributed by adjacent areas. Typically, grab strength is determined on a 12-in.-wide strip of fabric, with the tensile load applied at the midpoint of the fabric width through 1-in.-wide jaw faces.

gradient ratio,
the ratio of the average hydraulic gradient across the fabric and the 1 in. of soil immediately next to the fabric to the average hydraulic gradient across the 2 in. of soil between 1 and 3 in. above the fabric, as measured in a constant head permeability test.

heat bonding,
a process by which fabric filaments are welded together at their contact points by subjection to a relatively high temperature.

heat seaming,
the process of joining two or more thermoplastic films of sheets by heating areas in contact with each other to the temperature at which fusion occurs. The process is usually aided by a controlled pressure. In dielectric seaming the heat is induced with in films by means of radio-fregency waves.

hydrophillic,
a material's attraction to water.

hydrophobic,
a material's repulsion of water.

impact resistance,
resistance to fracture under shock force.

in-plane,
the direction of a geosynthetic which is parallel to its long, manufactured, or machine direction. Referred to in hydraulic situations.

knit,
See Fabric, knit.

knitted fabric,
a textile made up of loops of fibers connected by straight segments.

lapped joint,
a joint made by placing one surface to be joined partly over another surface and bonding the overlapping portions.

lateral restraint reinforcement,
the action of increasing the ultimate bearing capacity and load-deformation modulus of soil placed over fabric through the mechanism of fabric resistance to cover material horizontal movement, thereby increasing the modular ratio of the system.

length, bending,
general: a measure of the interaction between geotextile weight and fabric stiffness as shown by the way in which a geotextile blends under its own weight. It reflects the stiffness of a geotextile when bent in one plane under the force of gravity and is one component of drape. NOTE: bending length is called drape stiffness in Federal Specification CCC-T-19 1b, Textile Test Methods No. 5206.2.
specific: the cube root of the ratio of the flexural rigidity to the weight per unit area.

leno fabric,
an open fabric in which two warp yarns wrap around each fill yarn to prevent the warp or fill yarns from sliding over each other.

machine direction,
the axis within the plane of the fabric parallel to the direction in which a fabric is processed onto rolls as the final step of production.

mass per unit area,
the proper term to represented and compare to amount of material per unit area (units are oz/yd^2 or g/m^2).

melt bonding,
see heat bonding.

membrane,
in this book the term applies to a continuous sheet of material, whether prefabricated as a flexible polymeric sheeting or sprayed or coated in the field, such as a sprayed-on asphalt.

membrane-type fabric support,
additional roadway support capacity gained from the vertical resultant of fabric tensile stresses developed as the result of subgrade rutting.

modular ratio,
the ratio of the deformation modulus of a layer of material to the deformation modulus of an underlying material.

modular ratio effects,
the decrease in stresses transmitted to a road subgrade, corresponding to increase modular ratio and vice versa.

modulus,
the stress on stretching a material to different elongations (e.g., E_{100} and E_{200}).

modulus of elasticity,
the ratio of stress to strain within the elastic range, also known as Young's modulus.

monofilament,
a single filament of a man-made fiber, usually of a denier higher than 15.

multiaxial tensil test,
a tensile test in which a fabric specimen is subjected to tensile forces in more than two directions.

multifilament,
a yarn consisting of many continuous filaments or strands.

needle punched,
mechanically bonded by needling with barbed needles.

needle punching,
subjecting a web of fibers to repeated entry of barbed needles that compact and entangle individual fibers to form a fabric.

neoprene (polychloroprene),
generic name for a synthetic rubber, based primarily on chloroprene (i.e., chlorobutadiene). Vulcanized generally with metal oxide. Resistant to ozone and aging and to some oils.

nitrile rubber,
a family of copolymers of butadiene and acrylonitrile that can be vulcanized into tough oil-resistant compounds. Blends with PVC are used where ozone and weathering are important requirements in addition to its inherent oil and fuel resistance.

nonwoven fabric,
a textile structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, chemical, or solvent means.

normal direction,
for geotextiles, the direction perpendicular to the plane of a geotextile.

nylon,
generic name for a family of polyamide polymers characterized by the presence of the amide group - $CONH_2$. Used as ascrim in fabric-reinforced sheeting.

offset tangent modulus,
a tensile stress-strain modulus obtained using a straight line to represent the stress-strain curve drawn parallel to and offset by a prescribed distance from a line tangent to the initial portion of the actual stress-strain curve.

open area,
that portion of the plane of the fabric in which there are no filaments, fibers, or films between the upper and lower surfaces of the fabric. This is expressed as a percentage of the total area.

optimum depth,
the thickness of engineering fabric cover material, in a road system, which will result in development of maximum reinforcement potential of the cover material.

penetration resistance,
the fabric property determined by the force required to penetrate a fabric with a sharp pointed object. Initial pentration is by separating the fibers. Further penetration is essentially a tearing process.

percent open area,
the net area of a fabric that is not occupied by fabric filaments, normally determinable only for woven and non-woven fabrics having distinct visbile and measureable openings that continue directly through the fabric.

permeability,
(1) a generic term for the property that reflects the ability of a material to conduct a fluid. (2) the capacity of a porous medium to conduct or transmit fluids. (3) the amount of liquid moving through a barrier in a unit time, unit area, and unit pressure gradient not normalized for but directly related to thickness.

permeability (longitudinal or in plane),
the fabric property which permits water to be transmitted in the plane of the fabric.

permeability (transverse),
the fabric property which allows water to pass through perpendicular to the plane of the fabric.

permittivity,
for a geotextile, the volumetric flow rate of water per unit cross section area, per unit head, under laminar flow conditions, in the normal direction through a material.

piping,
the process by which soil particles are washed in or through pore spaces in drains and filters.

plastic,
a material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and at some stage in its manufacture or processing into finished articles, can be shaped by flow.

plasticizer,
a plasticizer is a material, frequently "solventlike," incorporated in a plastic or a rubber to increase its ease of workability, its flexibility, or distensibility. Adding the plasticizer may lower the melt viscosity, the temperature of the second-order transition, or the elastic modulus of the polymers (EVA). The most important use of plasticizers is with PVC, where the choice of plasticizer will dictate under what conditions the liner may be used.

polyester fiber,
generic name for a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of an ester of a dihydric alcohol and terephthalic acid. Scrims made of polyester fibers are used for fabric reinforcement.

polymer,
a macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high-molecular-weight polymers.

polymeric liner,
plastic or rubber sheeting used to line disposal sites, pits, ponds, lagoons, canals, and so on.

polyvinyl chloride (PVC),
a synthetic thermoplastic polymer prepared from vinylchloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes adn well screens; flexible forms used in manufacture of sheeting.

pore size,
the size of an opening between fabric filaments because of the variability of opening sizes; equivalent opening size (EOS) is used to quantify this fabric property.

porosity,
the ratio of the volume of void space to the total volume. NOTE: Usually expressed as a percentage of the volume.

puncture,
the rupture of a fabric by a force normal to the fabric plane while the fabric is constrained in all directions in that plane, applied by a small diameter object.

puncture resistance,
extent to which a material is able to withstand the action of a sharp object without perforation. Examples of test of this property are Federal Test Methods Stnadard No. 101B, Methods 2031 or 2065.

reinforcement,
strengthening of a soil-fabric system by contributions of the fabric inclusion.

resin bonded,
the joining of fibers at their intersection points by resin in the formation of a nonwoven geotextile or geocomposite.

resin bonding,
the fabric web is impregnated with a resin which serves to coat and cement the fibers together.

roll goods,
a general term applied to rubber and plastic sheeting, whether fabric reinforced or not. It is usually furnished in rolls.

rubber,
a polymeric material which, at room temperatur, is capable of recovering substantially in shape and size after removal of a deforming force. Refers to both synthetic and natural rubber, also called an elastomer.

scrim,
a woven, open-mesh reinforcing fabric made from continuous-filament yarn. Used in the reinforcement of polymeric sheeting.

seam strength,
strength of a seam of liner material measured either in shear or peel modes. Strength of the seams is reported either in absolute units (e.g., pounds per inch of width) or as a percent of the strength of the sheeting.

secant modulus,
a tensile stress-strain modulus obtained using a straight line (to represent the stress-strain curve) drawn from the origin through a coordinate representing a stress measured at a specified strain.

separation,
function of fabric as a partition between two adjacent materials to prevent mixing of the two materials.

sheeting,
a form of plastic or rubber in which the thickness is very small in proportion to length and width and in which the polymer compound is present as a continuous phase throughtout, with **staple,**
short fibers in the range 0.5 to 3.0 in.

soil-fabric friction,
the resistance to sliding between engineering fabric and soil, excluding the resistance from soil cohesion. Soil-fabric friction is usually quantified in terms of a friction angle.

specific gravity,
the ratio of the density of a fabric to the density of water obtained by weighting both items in air. A specific gravity less than one implies that the fabric will float.

spun-bonded fabrics,
fabrics formed by continuous filaments which have been extruded and drawn.

staple yarn,
yarn made from staple fibers.

stiffness,
the ability of a fabric to resist bending when flexural stress is applied.

strain,
the change in length per unit of length in a direction.

strength, bursting,
a measure of the ability of a fabric to resist rupture by a force normal to the fabric plane when applied over an area of 6.0 cm^2 while the fabric is constrained in all directions in that plane.

strength, tearing, F, (F),
the force required either 1) to start or 2) to continue or propogate a tear in a fabric under specified conditions.

stiffness,
resistance to bending.

strikethrough,
a term used in the manufacture of fabric-reinforced polymeric sheeting to indicate that two layers of polymer have made bonding contact through the scrim.

strip tensile test,
a uniaxial tensile test in which the total width of a fabric of prescribed dimensions is gripped prior to subjecting to tensile forces.

subgrade intrusion,
localized aggregate penetration of a soft cohesive subgrade and resulting displacement of the subgrade into the cohesionless material.

subgrade pumping,
the displacement of cohesive or low-cohesion fines from a saturated subgrad into overlying aggregate, as the result of hydraulic forces created by transmittal of wheel-load stresses to the subgrade.

supported sheeting,
See Fabric reinforcement.

surface cure,
curing or vulcanization which occurs in a thin layer on the surface of a manufactured polymeric sheet or other items.

survivability,
the ability of a fabric to be placed and to perform its intended function without undergoing degradation.

syphoning,
the transferring of a liquid to a lower level over an intermediate higher elevation than both of the endpoints, which can be achieved by saturated geotextiles in planar flow.

tangent modulus,
a tensile stress-strain modulus obtained using a straightline (to represent the stress-strain curve) drawn tangent to a specified portion of the stress-strain curve.

tear strength,
the maximum force required to tear a specified specimen, the force acting substantially parallel to the major axis of the test specimen. Measured in both initiated and uninitiated modes. Obtained value is dependent on specimen geometry, rate of extension, and type of fabric reinforcement. Values are reported in force (e.g., pounds) or force per unit of thickness (e.g., pounds per inch).

tenacity,
the fiber strength on a grams per denier basis.

tensile modulus,
see tensile stress-strained modulus.

tensile strength,
the strength shown by a fabric subjected to tension as distinct from torsion, compression, or shear.

tensile strength-strain modulus,
a measure of the resistance to elongation under stress. The ratio of the change in tensile stress to the corresponding change in strain.

test, tensile,
in textiles, a test in which a textile material is stretched to determine the force-elongation characteristics, the breaking force, or the breaking elongation.

tests, wide-width strip tensile,
for geotextiles, a uniaxial tensile test in which the entire width of a specimen is gripped in the clamps and is greater than the gage length.

tex,
denier divided by 9.

textile,
orginally a woven fabric, now generally applied to:

1) staple fibers and filaments suitable for conversion to or use as yarns, or for the preparation of non-woven fabrics.
2) yarns made from natural or manmade fibers.
3) fabrics and other manufactured products made from fibers as defined above and from yarns.

thermal shrinkage,
for a geotextile decrease in length, in width, or both as measure in the atmosphere for testing geotetiles or an unrestrained specimen that has been subjected to a specified temperature for a specified length of time.

thermal stability,
the ability of fibers and yarns to resist degradation at extreme temperatures.

thermoplastic,
capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature. Most polymeric liners are supplied in thermoplastic form because the thermoplastic form allows for easier seaming both in the factory and on the field.

thermoplastic elastomers,
new materials which are being developed and which are probably related to elasticized polyolefins. Polymers of this type behave similarly to cross-linked rubber. They have a limited upper-temperature service range which, however, is substantially above the temperature encountered in waste disposal sites (200°F may be too high for some TPEs).

thickness,
the normal distance between two surfaces of a fabric. NOTE: Thickness is usually determined as the distance between an anvil, or base, and a pressure foot used to apply a specified compressive stress.

thickness,
thickness under a specified stress applied normal to the material.

thickness nominal, t_g, (L),
of a geotextile, thickness under a compressive stress of 2.0 kPA applied normal to the material.

thread count,
the number of threads per inch in each direction with the warp mentioned first and the fill second (e.g., a thread count of 20 x 10 means 20 threads per inch in the warp and 10 threads per inch in the fill direction).

toughness, breaking, T, (E/m),
for geotextiles, the actual work per unit surface area of material that is required to rupture the material. It is proportional to the area under the load-elongation curve from the origin to the breaking point (see also work-to-break). Discussion: for geotextiles, breaking toughness is calculated from work-to-break, gage length, and width of a specimen or specific work-to-break divided by the width.

transmissivity,
for a geotextile, the volumetric flow rate per unit thickness under laminar flow conditions, in the in-plane direction of the fabric.

transverse direction,
deprecated term (see direction, cross machine).

ultraviolet (UV) radiation stability,
the ability of fabric to resist deterioration from exposure to sunlight.

ultrimate elongation,
the elongation of a stretched specimen at the time of break. Usually reported as percent of the original length. Also called elongation at break.

ultraviolet degradation,
the breakdown of polymeric structure when exposed to light.

uniaxial tensile test,
a tensile test in which a fabric specimen is subjected to tensile forces in one direction.

unsupported sheeting,
a polymeric sheeting consisting of one or more plies without a reinforcing-fabric layer or scrim.

upstream,
the direction on the near side of a geotextile from which water is moving.

vacuum box,
a device used to assess the integrity of field seams in membrane liners.

void ratio, e,
the ratio of the volume of void space to the volume of solids. NOTE: In a geotextile, the solids are assumed incompressible and include fibers, yarns, binders and combinations thereof, if present.

voids,
the open spaces in a geosynthetic material through which flow can occur.

vulcanize,
used to demote the product of the vulcanization of a rubber compound without reference to shape or form.

warp,
fibers or yarns parallel to the fabric machine direction.

warp direction,
see direction, machine. NOTE: this term is commonly used for woven fabrics only.

water vapor transmission (WVT),
water vapor flow normal to two parallel surfaces of a material, through a unit area, under the conditions of a specified test such as ASTM E96.

web,
the sheet or mat of fibers or filaments before bonding or needle punching to form a nonwoven fabric.

weft,
deprecated term (see direction, cross machine).

width, w, (L),
for a geotextile, the cross direction edge-to-edge measurement of a fabric in a relaxed condition on a flat surface.

woof,
deprecated term (see direction, cross machine).

workability,
the abilityof a fabric to be easily handled, layed, and sewn, and further simplify construction procedures.

work-to-break, W, (LF),
in tensile testing, the total energy required to rupture a specimen. Discussion: For geotextiles, work-to-break is proportional to the area under the load-elongation curve from the origin to the breaking point.

woven fabric,
a textile structure comprising two or more sets of filaments of yarns interlaced in such a way that the elements pass each other essentially at right angles and one set of elements is parallel to the fabric axis.

woven, monofilament,
woven fabric produced with monofilament yarns.

woven, multifilament,
the woven fabric produced with multifilament yarns.

woven, slit film,
the woven fabric produced with yarns produced from slit film.

woven, split film,
woven fabric produced with yarns produced from split film.

yarn,
a generic term for cintinuous strands of textile fibers or filaments in a form suitable for knitting, weaving, or otherwise intertwining, to form a textile fabric. It may comprise (1) a number of fibers twisted together, (2) a number of filaments laid together without twist (a zero-twist yarn), (3) a number of filaments laid together with more or less twist, or (4) a single filament with or without twist (a monofilament).

APPENDIX C - INDEX PROPERTIES

I GEOMEMBRANES

PAGE

Water Absorption/Moisture Content, ASTM D570 CI-1
Flow Rate of Thermoplastics, ASTM D1238 CI-2
Density/Specific Gravity, ASTM D792 CI-3
Carbon Black Content and Concentration, ASTM 1603 CI-4
Pigment Dispersion in Plastics, ASTM D3015 CI-5
Nominal Thickness, ATSM D751 CI-6
Durometer Hardness, ASTM D2240 CI-7
Dimensional Stability, ASTM D1204 CI-8
Heat Deterioration of Rubber, ASTM D573 CI-9
Thermal Expansion, ASTM D696 CI-10
Volatile Loss from Plastics, D1203 CI-11
Brittleness Temperature, ASTM D746 CI-12
Ozone Resistance, ASTM D1149 CI-13
Puncture Strength, Proposed ASTM CI-14
Impact Resistance, Proposed ASTM CI-15
Tearing Resistance, ASTM D1004 CI-16
Breaking Load and Extension, ASTM D638 CI-17
Water Vapor Transmission, ASTM E96 CI-18
Burial Degradation, ASTM D3083 CI-19
Environmental Stress Cracking, ASTM D1693 CI-20
Environmental Stress Rupture, ASTM D2552 CI-21
Peel Adhesion of Geomembrane Seams, ASTM D413 CI-22

II GEOTEXTILES

Grab Tensile Strength, ASTM D4632 CII-23
Strip Tensile Strength,ASTM D1682 CII-24
Hydrostatic Bursting Strength, ASTM D751 CII-25
Tearing Strength (Trapezoidal), ASTM D4533 CII-26
Abrasion Resistance, Proposed ASTM CII-27
Pore (Opening) Size, Proposed ASTM CII-28
Degradation From Exposure to Ultraviolet Light ASTM D4355 CII-29
Temperature Stability, ASTM D4594 CII-30
Water Permeability (Permittity), ASTM D4491 CII-31
Compression Behavior/Crush Strength, Proposed ASTM CII-32

INDEX PROPERTY: WATER ABSORPTION/MOISTURE CONTENT OF PLASTICS
REFERENCED TEST METHOD: ASTM D570
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANES OR RAW MATERIALS FOR GEOMEMBRANES AND GEONETS
TARGET VALUE: PERCENT OF WATER ABSORBED
UNITS: Percent

SUMMARY OF METHOD:

This test method is used as an index test to determine the water absorption of finished geomembranes or to determine the moisture content of resins used in the manufacture of geomembranes and geonets. The moisture content and the water absorption may be an indicator of mechanical properties of the finished product. The procedure may not be suitable for scrim-reinforced geomembranes.

Specimens may consist of pellets, bars, tubes or sheets. For water absorption tests, the specimens are first dried in an oven at a temperature ranging from 50 to 100°C (depending on temperature stability of the specimen) for a period of 24 hours. After this drying period, the specimens are weighed. The specimens are then immersed in distilled water for a specific period of time (2-hour, 24-hour, or long-term) at a temperature specified in the test method. After the immersion period, the specimen is removed and again weighed. The water absorption is the increase in weight, expressed as a precent of dry specimen weight.

For moisture content determination, the "as received" specimen surface is dried and then the specimen is weighed. The specimen is then dried in an oven for 24 hours, removed and weighed. The moisture content is the change in specimen weight, expressed as a percent of the "as received" weight.

TEST EQUIPMENT:

Scale (±0.001 gm) and oven (50-110°C).

INDEX PROPERTY: FLOW RATE OF THERMOPLASTICS
REFERENCED TEST METHOD: ASTM D1238 (Method A - Manual Method)
ALTERNATIVE METHODS: ---
SCOPE: THERMOPLASTIC RESINS FOR GEOMEMBRANES, GEONETS AND GEOGRIDS
TARGET VALUE: MELT FLOW INDEX
UNITS: gm/10 min.

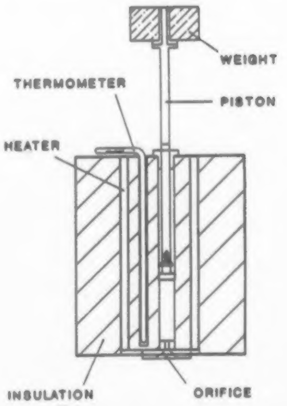
SUMMARY OF METHOD:

The Melt Flow Index is an empirical indicator of the uniformity of polymer resins such as polyethylene and polypropylene or finished goods made from these polymer resins. The test is essentially a quality control test for thermoplastics but may be indicative of the uniformity of other mechanical properties of the specimen or other specimen types produced using identical processes.

The specimens consist of powered, film strips or pellets of resin. The test conditions, including test temperature, load or pressure, are selected from appropriate material specifications. Two or more conditions are generally required. The test cylinder and plastometer are preheated to the specified temperature, which ranges from 125 to 315°C (257 to 600°F). The piston is removed from the cylinder and a prescribed weight of specimen (depending on the expected flow rate) is placed into the cylinder. The weighted piston is replaced into the cylinder and the entire apparatus is preheated from 6 to 8 minutes. The specimen is purged from the cylinder and is extruded from the base. The amount or rate of purge is regulated to ensure scribe marks on the piston are at the proper reference start position as outlined in the test method. When the start position requirements are met, timed extrudates are collected (between 6 and 8 minutes from charging) at prescribed time intervals. Each extrudate is weighed. The extrudate weight is multiplied by the factor listed in the test method to obtain the flow rate in grams per 10 minutes. Clean the apparatus and repeat the procedure under other test conditions if required.

TEST EQUIPMENT:

Plastometer, cylinder and piston materials and details are shown in test method for manual and automatic equipment.



INDEX PROPERTY: DENSITY/SPECIFIC GRAVITY
REFERENCED TEST METHOD: ASTM D792 (Method A1)
ALTERNATIVE METHODS: ---
SCOPE: GEOSYNTHETICS RAW MATERIAL RESINS OR GEOMEMBRANE SHEET
TARGET VALUE: DENSITY OR SPECIFIC GRAVITY
UNITS: gm/cc or dimensionless

SUMMARY OF METHOD:

The above test method covers the determination of density and specific gravity of solid plastic sheets, rods, pellets, etc. The test can be performed on raw polymer material (such as a polyester for geomembranes) or finished products such as geomembranes. Specimens are removed in a random fashion from homogeneous laboratory samples. All specimens are conditioned at a specific constant temperature and relative humidity for not less than 40 hours prior to testing. The tests are performed at a temperature of 23±2°C (73°F) and 50±% relative humidity.

Specimens mass can be anywhere from 1 to 50 g. The immersion media is normally water unless the specimen is prone to physical changes upon contact with water. The specimen is first weighed in air to the nearest 0.1 mg. The method involves suspending the plastic specimen from a scale and completely immersing the specimen in desired distilled or demineralized water. A sinker may be attached to the specimen if it is lighter than water. All air bubbles are carefully removed, and the immersed specimen and sinker (if used) are weighed while immersed. The specific gravity is the ratio of the apparent weight of the specimen in air to the difference of the specimen dry and wet weights at a temperature of 23°C. The density (gm/cc) is calculated by multiplying the specific gravity by a conversion factor of 0.9975.

TEST EQUIPMENT:

Analytical Balance with precision within 0.1 mg, corrosion resistant wire, sinker and immersion (usually glass) vessel.

INDEX PROPERTY: CARBON BLACK CONTENT AND CONCENTRATION
REFERENCED TEST METHOD: ASTM D1603
ALTERNATIVE METHODS: ---
SCOPE: POLYETHYLENE GEOMEMBRANES, GEONETS OR GEOGRIDS
TARGET VALUE: CARBON BLACK CONTENT AND CONCENTRATION
UNITS: % and g/cc

SUMMARY OF METHOD:

The referenced method covers the determination of carbon black content and density for quality control testing of polyethylene, polypropylene, and some other plastics. The assembly of the apparatus is illustrated in the test method. A small porcelain boat is heated using a bunsen burner, placed in a dessicant (such as calcium chloride) and allowed to cool for at least 30 minutes. The boat is then weighed. Approximately one gram of plastic specimen is placed into the boat and weighed to determine the original specimen weight to the nearest 0.0001 g. The specimen and boat are heated for 15 minutes in a furnace up to 600°C under a constant flow of nitrogen. The specimen is allowed to cool for 5 minutes under the nitrogen flow and is then removed from the furnace and cooled in the dessicant for at least 30 minutes. The boat and specimen are again weighed to the nearest 0.0001 g to determine the residue mass. All tests are performed with duplicate specimens. The carbon black content is the residue mass divided by the initial specimen mass, expressed as a percent. The carbon black concentration (g/cc) is the product of the residual mass and the specimen density divided by the initial specimen mass.

TEST EQUIPMENT:

Furnace, combustion boat, drying tube and glass tubing, gas flow meter and reagents including dry ice, calcium chloride, nitrogen and trichloroethylene. Detailed descriptions of all reagents, materials and apparatus, are contained in the test method.

INDEX PROPERTY: PIGMENT DISPERSION IN PLASTICS
REFERENCED STANDARD PRACTICE: ASTM D3015
ALTERNATIVE METHODS: ---
SCOPE: THERMOPLASTIC GEOMEMBRANES
TARGET VALUE: CARBON BLACK DISPERSION
UNITS: Visual Comparison to Standard

SUMMARY OF METHOD:

The referenced Standard Practice covers the procedure for examining and grading plastic compounds to check quality of pigment (specifically carbon black) dispersion. Grading or classification of thin section specimens is performed by comparison against grade standards. Carbon black dispersion and quality, the presence of foreign matter or unpigmented resin, etc., can be an indicator of overall utility of the material in field applications. Only compounds that are translucent in thin sections (such as polyethylene) can be accurately examined. The observational standards for grading of the specimens are generally agreed upon between purchaser and seller, and are not included in the Standard Practice.

Six specimens, approximately 1.6 mm (0.063") in diameter, are removed from six separate compound samples. Thin sections are placed on a microscope slide at 10 mm (0.375") intervals, and a second slide is placed over the specimens. The assembly is placed on a hot plate which is controlled to a temperature suitable to press out the specimens to a uniform thickness and diameter. The slides are removed form the hot plate and allowed to cool. The specimen assembly is placed beneath a microscope and examined at a magnification of 100X. Each specimen is rated against the observational standard. Standards are numbered in ascending order from the best quality (one) to the worst quality. A minimum point of acceptability is usually set in a specification. Flaws, unpigmented areas, etc., are noted for each specimen.

TEST EQUIPMENT:

Microscope, slides, hot plate with pyrometer, and sectioning equipment.

INDEX PROPERTY: GEOSYNTHETIC NOMINAL THICKNESS
REFERENCED TEST METHOD: ASTM D751
ALTERNATIVE METHODS: ASTM D1593 (Indirect Method)
SCOPE: GEOMEMBRANES, GEONETS
TARGET VALUE: NOMINAL THICKNESS
UNITS: mm (inches or mils)

SUMMARY OF METHOD:

The referenced test method covers the determination of the nominal thickness of geosynthetic sheet of low compressibility such as geonets and most geomembranes The procedure is not recommended for highly compressible geosynthetics, such as nonwoven geotextiles or very open or thick geogrids or geocomposites. Geotextile thickness is proposed to be measured under a compressive stress of 2 kPa (0.29 psi).

The thickness is measured using a dead weight type thickness gage with a dial graduated to 0.025 mm (0.001"). The presser foot is circular having a diameter of 9.5 mm (0.375"). The thickness is measured under a normal compressive stress of 23.5 kPa (3.4 psi) after a seating period of 10 seconds. Similar measurements are made at least at five uniformly distributed locations throughout the sample. The reported thickness is the average of the five measurements.

TEST EQUIPMENT:

Thickness gage as described above.

INDEX PROPERTY: DUROMETER HARDNESS
REFERENCED TEST METHOD: ASTM D2240
ALTERNATIVE METHODS: NOTCHED (Charpy & IZOD)
ASTM D785 (Hard Plastics),
ASTM D1415 (Rubber)
SCOPE: ALL GEOMEMBRANES
TARGET VALUE: HARDNESS
UNITS: Dimensionless

SUMMARY OF METHOD:

The reference test method outlines the procedure to obtain the Shore type durometer hardness for geomembranes. Two types of durometers are described: Type A for softer materials (such as rubber) and Type D for harder materials, such as thermoplastics. The durometer hardness is an empirical test for quality control purposes. There may be no correlation between durometer hardness obtained from this method and values obtained using other methods, such as the Rockwell Hardness, ASTM D785.

The test specimen consists of a square measuring at least 25 mm (1") for single hardness determination. The specimen thickness is at least 6 mm (0.25"), which may be attained by stacking pieces of identical material providing that the surfaces between the plies are in complete contact. The test apparatus consists of a 2.5 to 3.2 mm (0.10 to 0.13") diameter presser foot, a steel indentor (for Type A or Type D) and an indicating device. The indicating device is graduated from zero, for full extension, to 100 for zero extension. A calibrated spring is attached to the indentor so that the force applied to the specimen is a known function of the hardness. Tests are run at 23° (73°F). The specimen is placed on a firm surface, and the durometer is held vertically so that the presser foot is parallel to the surface of the specimen. The scale on the indicator is read after the foot has been in contact with the specimen for 1 second unless a longer loading period is specified. The penetration is read directly from the gage. The hardness is determined from the calibration of the device for a known loading and penetration. The applicable force equations appear in the test method.

TEST EQUIPMENT:

Presser foot, indentor (Type A&D), indicating device and spring calibrating device. A sketch of the durometer spring calibrating device as well as details of the indentors are presented in the test method.

INDEX PROPERTY: DIMENSIONAL STABILITY
REFERENCED TEST METHOD: ASTM D1204
ALTERNATIVE METHODS: ---
SCOPE: THERMOPLASTIC GEOMEMBRANES
TARGET VALUE: CHANGE IN SPECIMEN DIMENSIONS
UNITS: %

SUMMARY OF METHOD:

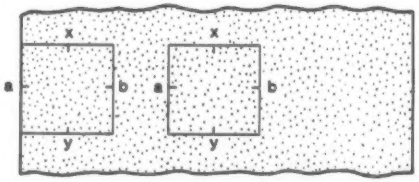
The referenced test method is intended as an index test to determine the dimensional stability of nonrigid plastic geomembrane specimens at specified elevated temperature and exposure time.

Two 250x250 mm (10"x10") specimens are removed from the laboratory sample by means of a cutting template or die. Each specimen is marked to show the direction of extrusion or callendering. The midpoint of each edge of the specimen is marked as a reference point for measuring. The specimens are conditioned and then placed on heavy flat paper dusted with talc to prevent restriction of the specimen expansion. A second layer of paper is placed over the specimen. The specimen is then placed in an oven. The temperature and exposure time are selected by the user or from an applicable material specification.

After removal from the ovens and reconditioning, the specimens are again measured to the nearest 0.25 mm (0.01"). The percent change (expansion) of the exposed specimen is recorded.

TEST EQUIPMENT:

Oven, scale, thermometer, specimen cutting die or template, heavy paper sheets and talc.



a,b,x,y MARK MIDPOINTS OF SPECIMEN

INDEX PROPERTY: HEAT DETERIORATION OF RUBBER
REFERENCED TEST METHOD: ASTM D573
ALTERNATIVE METHODS: ---
SCOPE: RUBBER GEOMEMBRANES
TARGET VALUE: CHANGE IN BREAKING STRENGTH
UNITS: %

SUMMARY OF METHOD:

The referenced method is a comparison test to determine the influence of elevated temperatures on the physical properties of vulcanized rubber. The dumbbell-shaped specimens are exposed to specified elevated temperatures in an air environment inside an oven. After a particular exposure time, the physical properties are determined and compared to control data. Tensile properties for the rubber specimens are determined as directed in ASTM D412. Three or more specimens are tested for each exposure period. Testing intervals are dependent on the type of rubber and the test temperature. Typical intervals are 2, 4, 7 and 14 days. At the end of the aging interval, the specimens are removed from the oven and allowed to cool at room temperature for at least 16 hours before properties tests are performed. The changes in tensile properties (breaking strength and elongation) are plotted against time or compared to the applicable material specifications.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) tensile testing device, specimen cutter, oven, temperature monitoring and control devices, and specimen rack.

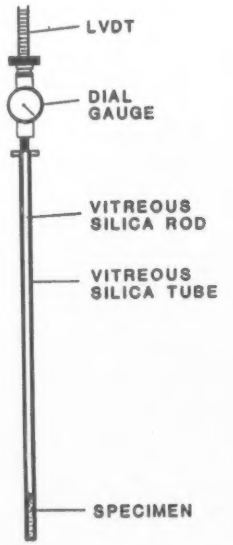
INDEX PROPERTY: THERMAL EXPANSION
REFERENCED TEST METHOD: ASTM D696
ALTERNATIVE METHODS: ---
SCOPE: CRYSTALLINE AND THERMOPLASTIC GEOMEMBRANES
TARGET VALUE: COEFFICIENT OF THERMAL EXPANSION
UNITS: Expansion per unit length per degree Celsius

The referenced test method covers the determination of the coefficient of linear thermal expansion of plastics over a specific range of temperatures. Thermal expansion is an elastic (recoverable) component of elongation of plastics. Other components include deformation caused by changes in moisture, phase changes, curing and stress relaxation. This test is conducted under conditions that reduce all other components except for thermal expansion or contraction. For this reason, the test yields only an approximation of true behavior.

Tests are conducted at temperatures of -30°C (-22°F) and 30°C (86°F). Conditioned specimens measuring 50x125 mm (2"x5") are placed within a fused-quartz-tube dilatometer which consists of two cylinder dilatometers. The net pressure on the specimen between the dilatometers is 70 kPa (10 psi). The apparatus is placed into a -30°C (-22°F) bath. Deformation of the specimen is measured using an LVDT or dial gage under constant temperature until there is no change in deformation after about 5 to 10 minutes. The procedure is repeated in a constant temperature of 30°C (86°F) and deformation is again recorded. The coefficient of thermal expansion is the change in length recorded due to heating or cooling divided by the product of the original specimen length and the temperature difference.

TEST EQUIPMENT:

Fused-quartz-tube dilatometer (details included in Test Method) LVDT or dial gage, constant temperature liquid bath and thermometer or thermocouple.



QUARTZ-TUBE DILATOMETER

INDEX PROPERTY: VOLATILE LOSS FROM PLASTICS
REFERENCED TEST METHOD: ASTM D1203
ALTERNATIVE METHODS: REFER TO ASTM E197
SCOPE: THERMOPLASTIC OR CRYSTALLINE GEOMEMBRANES
TARGET VALUE: WEIGHT LOSS
UNITS: %

SUMMARY OF METHOD:

This empirical method covers the determination of the volatile loss from a plastic material under specific temperature and time conditions using activated carbon as the immersion medium. Relative comparison of geomembrane specimens of the same nominal thickness can be conducted. Two methods are described. Method A is the direct contact method and Method B is the wire cage method, which may yield a more precise result.

Geomembrane specimens are 50 mm (2") diameter disks. After a conditioning period of at least 20 hours at 23°C (73°F) and 50% relative humidity, the specimen thickness and weight are measured. Three test specimens are used for each test. A specified volume of activated carbon is placed in the bottom of a 1-pint container. For Method A, layers of activated carbon are placed between each of the three specimens. For Method B, the wire cages are separated by layers of activated carbon. The container is sealed and placed in an oven at a temperature of 79°C (158°F) for a period of 24 hours. At the end of the heating period, the specimens are removed, brushed free of activated carbon, reconditioned for 20 hours, and reweighed. The volatile loss is expressed as the percent of weight loss before and after the heating period.

TEST EQUIPMENT:

Oven (or bath), containers (1-pint paint cans or screw top jars) balance, micrometer, metal cages (Method B), and activated carbon as specified in the test method.

INDEX PROPERTY: BRITTLENESS TEMPERATURE
REFERENCED TEST METHOD: ASTM D746 (Plastics)
ALTERNATIVE METHODS: ASTM D2137 (rubber and reinforced)
SCOPE: GEOMEMBRANES
TARGET VALUE: BRITTLENESS TEMPERATURE
UNITS: °C (°F)

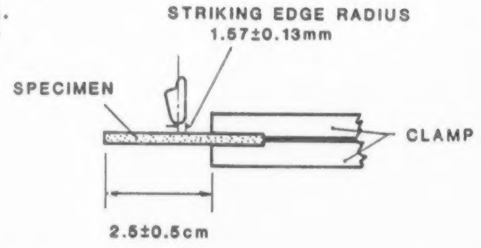
SUMMARY OF METHOD:

The referenced test method covers the determination of a temperature at which geomembrane specimens exhibit an impact failure under specified conditions. The method is essentially an index test but may be used to predict the behavior of specimens at low temperatures under similar loading and deformation conditions.

The test specimens are clamped at one end and held horizontally similar to a cantilever beam. The vertical striking member is released downward to impact the specimen with a striking edge having a radius of 1.57 mm (0.062"). A sketch of the striking member, clamp and specimen appear below. The specimen consists of a 6.4 mm (0.25") wide rectangle that is long enough to facilitate clamping plus allowing a 25 mm (1") extension. A minimum of ten specimens are tested at each test temperature. The specimens and clamp assembly are placed in a constant temperature bath for three minutes. The initial test temperature is selected at a temperature where a 50% failure rate is expected. Each specimen receives a single impact by the striking member. Each specimen is examined to determine if failure has occurred. The temperature is varied by 2 to 10°C increments until all 10 specimens fail at the lowest temperature and none of the ten specimens fail at the highest temperature. All test data (i.e., % failures vs. test temperature) is plotted and the brittleness temperature is defined as the temperature at which 50% of the specimens have failed. This is determined graphically.

TEST EQUIPMENT:

Constant temperature bath, temperature conducting, monitoring and controlling equipment, specimen clamp (drawing available from ASTM) and striking member.



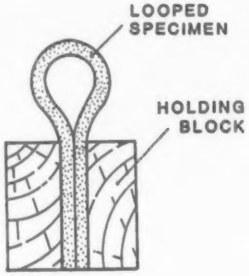
INDEX PROPERTY: OZONE RESISTANCE
REFERENCED TEST METHOD: ASTM D1149 (Lab Method)
ALTERNATIVE METHODS: ASTM D1171 (Outdoor Method for Soft Rubber)
SCOPE: RUBBER GEOMEMBRANES
TARGET VALUE: TIME TO CRACK FORMATION
UNITS: hours

SUMMARY OF METHOD:

The laboratory test method referenced is limited in scope to vulcanized rubber, although the applicability to other materials, such as plastics, is not addressed. The test method may not provide results consistent with real-time outdoor exposure. It provides a means of estimating the resistance of a rubber specimen to cracking when exposed to ozone under certain conditions in an enclosed chamber. Since ozone attack is related to - termperature, ozone concentration, stress relaxation of the specimens, etc., this test method is recommended only as a comparison between candidate materials tested under identical conditions. The test chamber has a minimum volume of 0.11 to 0.14 m^3 (4 to 5 ft.^{3}) and is capable of generating and maintaining an air-ozone stream of constant rate and ozone concentration. The air-ozone mix is circulated over the test specimens at a temperature of 40°C(104°F) or any temperature selected by the user. The standard ozone partial pressures are 25, 50, 100 and 200mPa, or as selected by the user. Test specimens can consist of a rectangular strip, a bent loop, or a tapered strip. The specimens are placed into grips at prescribed elongations ranging from 10 to 20% for the rectangular and tapered strip specimens. The specimens are inspected daily (more often for special tests) under a recommended magnification of 7x to detect the appearance of ozone cracking. The time to first observed cracking and the specific test conditions are reported.

TEST EQUIPMENT:

Ozone chamber as described in the test method, Ozone Generator, such as a mercury vapor lamp, and all associated circulation and monitoring equipment. Commercial equipment is available, but a source is not listed in the test method.



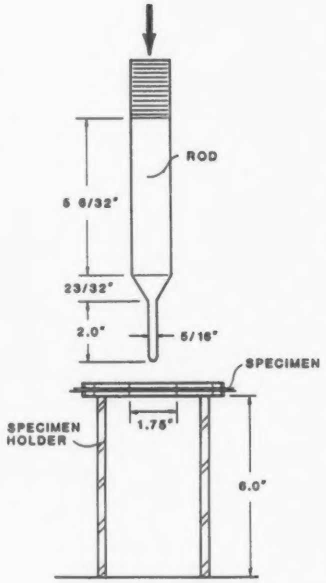
INDEX PROPERTY: PUNCTURE STRENGTH
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: CBR PLUNGER (DIN 54307)
SCOPE: GEOTEXTILES, GEOMEMBRANES, GEOCOMPOSITES
TARGET VALUE: PUNCTURE STRENGTH
UNITS: N (lbf)

SUMMARY OF METHOD:

The test specimen is placed between horizontal ring clamps without pretensioning. The attachment is placed within a constant-rate-of extension tensile testing device. The exposed area of the specimen is 45 mm (1.75") in diameter. A solid steel 8 mm (5/16") diameter rod with a 45° camfered edge is used to puncture the specimen. The test is performed at a rate of rod travel of 305 mm (12") per minute. The ultimate load (or double peak loads for geocomposites) is recorded as the specimen puncture strength. The number of specimens is determined by selecting the 95% probability level, but 15 specimens per test is considered to be the upper bound number.

TEST EQUIPMENT:

Drawings of rod and ring clamp attachments will be available through ASTM. CRE tensile testing device required.



INDEX PROPERTY: IMPACT RESISTANCE
REFERENCED TEST METHOD: ASTM PROPOSED
ALTERNATIVE METHODS: NOTCHED (Charpy & IZOD)
ASTM D256, DROP CONE METHODS
SCOPE: GEOTEXTILES, GEOMEMBRANES, SOME GEOCOMPOSITES
TARGET VALUE: IMPACT RESISTANCE (ENERGY)
UNITS: Joules (ft-lbf)

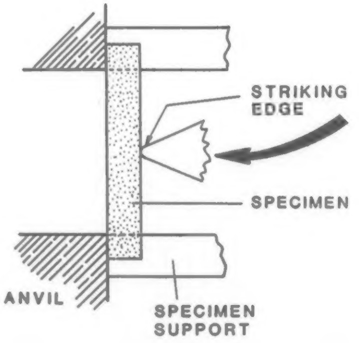
SUMMARY OF METHOD:

The proposed ASTM test method describes the pendulum impact-type test for geomembranes, geotextiles and some geocomposites. The test is not suitable for geonets or geogrids. The energy required to penetrate or rupture the specimen is applied by a cone having a specific weight and drop height. The rupture energy is read directly from the device, which is calibrated to read zero impact energy when no specimen is in the holder.

The geosynthetic specimens measure 250 mm x 100 mm (10"x4"), and are clamped on three sides to allow unimpeded passage of the cone. A minimum of five specimens are tested at a temperature of 23°C (73°F). The impact cone consists of detachable steel. The diameter is 25 mm (1"), the cone angle of attach (to the central axis) is 30°. The cone weight and the drop height are adjusted such that the combination of the two results in full penetration of the specimen by the impact cone. The specimen is inspected after full penetration to identify the type of failure (i.e., tear rupture, punching rupture or punching tear rupture) and to assure that slippage from the clamps has not occurred. The impact resistance is expressed as the average impact energy recorded for five specimens.

TEST EQUIPMENT:

Riehle or Wiedemann-Baldwin test device proposed. No additional information on equipment specifications are available at this time.



INDEX PROPERTY: TEARING RESISTANCE
REFERENCED TEST METHOD: ASTM D1004
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANES
TARGET VALUE: TEARING STRENGTH
UNITS: kN (lbf)

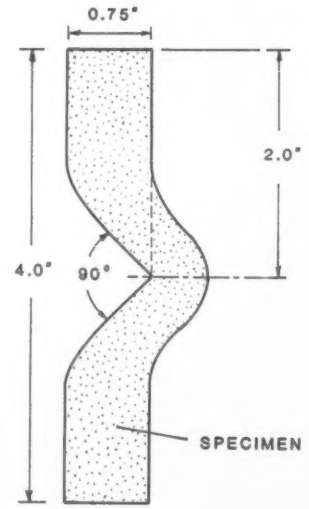
SUMMARY OF METHOD:

The referenced test method covers the determination of the tearing resistance of flexible plastic specimens using the specimen geometry shown below. This index test is used to measure the maximum force required to initiate a tear, and can be used to compare candidate geomembranes.

The specimens are placed within the jaws of a Constant-Rate-of-Extension (CRE) Tensile Testing Device after a conditioning period. The specimens are pulled to failure at a constant rate of 50 mm/min (2"/min). At least 10 specimens are tested in each direction of anisotropy. Specimens that exhibit failure at the jaws are discarded. The tearing resistance is reported as the average maximum recorded force for the specimens tested.

TEST EQUIPMENT:

CRE Tensile Testing Device, grips, thickness gauge and cutting die for the specimen detailed in the test method.



INDEX PROPERTY: BREAKING LOAD AND EXTENSION
REFERENCED TEST METHOD: ASTM D638
ALTERNATIVE METHODS: ASTM D882 (Thin Plastics)
ASTM D412 (Rubber)
SCOPE: THERMOPLASTIC OR CRYSTALLINE GEOMEMBRANES
TARGET VALUE: TENSILE STRENGTH AND ELONGATION
UNITS: kPa (psi) and %

SUMMARY OF METHOD:

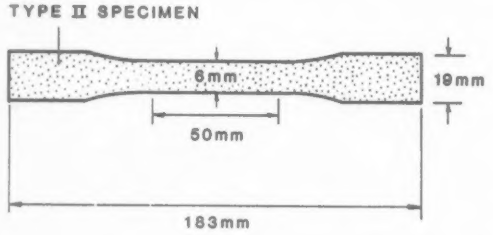
The referenced test method covers the determination of the tensile properties of plastic dumbbell-shaped specimens as thick as 14 mm (0.55"). For geomembranes less than 1 mm (40 mil) thick, ASTM D882 is the preferred method. The test is essentially an index test, although under certain testing conditions, it may yield design oriented data.

The specimen sizes are selected based on the type of material tested and its thickness. Five dumbbell type specimens ranging in narrow section width from 6 to 19 mm (0.25 to 0.75") are presented in the test method. Preparation of test specimens using a die cutter is recommended. All specimens are conditioned for a period of at least 40 hours prior to testing in a Constant-Rate of-Extension (CRE) tensile testing device. For isotropic materials, 5 specimens are tested for each sample. For anisotropic samples, 5 specimens are removed in each of the principal directions of anisotropy. Specimens are loaded to failure at rates specified in the test method in order to cause failure between 0.5 to 5 minutes testing time. Specimens that break at the jaws or along an obvious flaw are discarded.

The average tensile strength at yield and break is the yield or breaking load divided by the original minimum specimen cross sectional area. The modulus of elasticity can also be calculated as directed in the test method.

TEST EQUIPMENT:

CRE Tensile Testing Device, grips, extension indicator, and specimen die cutter.



INDEX PROPERTY: WATER VAPOR TRANSMISSION
REFERENCED TEST METHOD: ASTM E96
ALTERNATIVE METHODS: ---
SCOPE: ALL GEOMEMBRANES
TARGET VALUE: PERMEANCE
UNITS: metric perm

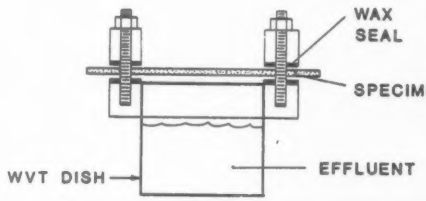
SUMMARY OF METHOD:

The referenced test method covers the determination of the rate of water vapor transmission (WVT) of sheet geomembranes under specified test conditions. The water vapor permeance of a specimen is the rate of WVT to the vapor pressure difference between the two outer surfaces of the specimen in units of a metric perm. The water vapor permeability for a homogenous material is the product of the permeance and the specimen thickness, and is expressed in units of metric perm-centimeter.

The test consists of several methods, each performed under specific temperature and relative humidities. In one procedure a dessicant (generally anhydrous calcium chloride) is placed within a dish which is completely covered by the specimen and sealed to prevent movement of water vapor except through the specimen. The environment outside the specimen is maintained at a temperature of 23°C (73°F) and a relative humidity of 50%. The change in relative humidity across the specimen (0% inside dish, 50% outside dish) is the driving force of water vapor transmission through the specimen. An alternate method involves filling the dish with water (relative humidity 100%) and covering the dish with the specimen. The environment outside the specimen is maintained at a relative humidity of 50% to again generate WVT. The WVT is measured by successive weighings of the specimen and dish over time (under the controlled test conditions). The results of the weighing of three specimens for each test method performed is plotted. When a straight line fits (within weighing error) four properly spaced points (i.e., a steady state exists), the slope of this line is the rate of WVT. The required conversion factors and calculations for determining permeance and permeability are provided in the test method.

TEST EQUIPMENT:

Environmental test chamber as described in the test procedure with capability to continuously record and adjust temperature and relative humidity. Test dishes, sealant and dessicant. Details of test dishes and sealing methods are provided in the Appendix of ASTM E96.



INDEX PROPERTY: BURIAL DEGRADATION
REFERENCED TEST METHOD: ASTM D3083
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANES
TARGET VALUE: TENSILE STRENGTH RETAINED
UNITS: %

SUMMARY OF METHOD:

The referenced test method is included in a general specification for PVC sheeting. Because of the relatively short burial period (30 days) and limited soil conditions examined, the referenced test method is not suitable as a design aid.

Three 25 x 150 mm (1x6") specimens are prepared in the machine and cross machine direction. The specimens are buried to a depth of 5" in soil "that is rich in cellulose-destroying microorganisms" for a period of 30 days. At the end of 30 days, the specimens are removed and tested in accordance with ASTM D882 and compared to the tensile strength of control (unburied) specimens.

The test may also be performed in a soil compost (pH of 6.5 to 7.5, moisture content between 25 and 30% and constant temperature between 32 and 38°C). The specimens are removed and percent of tensile strength retained is calculated.

TEST EQUIPMENT:

Greenhouse type apparatus capable of maintaining the test conditions listed above and Constant-Rate-of-Extension (CRE) Tensile Testing Device.

INDEX PROPERTY: ENVIRONMENTAL STRESS CRACKING
REFERENCED TEST METHOD: ASTM D1693
ALTERNATIVE METHODS: ---
SCOPE: THERMOPLASTIC GEOMEMBRANES
TARGET VALUE: PROPORTION OF FAILED SPECIMENS
UNITS: %

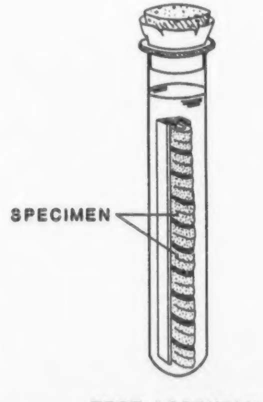
SUMMARY OF METHOD:

The referenced test method was developed to cover the determination of the susceptibility of ethylene plastics to environmental stress cracking under specified conditions. Environmental stress cracking of a geomembrane is highly dependent on the stress history and conditions of the specimen and on the nature of the reagent used. Under certain conditions, an indication of the performance of the specimen can be obtained. Generally, the method is used as an index test.

Test conditions such as specimen thickness, notch depth and test temperature are selected by the user from the three standard conditions listed in the test method. Rectangular specimens measuring 30x13 mm (1.5x0.5") are removed from the sample using a cutting die. Each conditioned specimen receives a notch on one surface using a special nicking jig. Ten specimens are placed in a bending clamp (see Figure) with the notch facing upward. The specimens are placed inside a test tube containing the reagent to be used during testing. The reagent may be a surface-active soap, such as Igepal CO-630, or any liquid organic that is not absorbed by the specimen. For special testing, the end use waste fluid can be used as the test reagent if the concentration can be controlled during testing at elevated temperature. The specimens are inspected at the end of the immersion period which is set at 48 hours in the absence of any other material specifications. The number of failures (any crack visible to the naked eye) is recorded and expressed as the percent of total number of specimens tested.

TEST EQUIPMENT:

Specimen cutting die, nicking jig, specimen holders, test tubes, reagent and constant temperature bath. Detail drawings of test apparatus are available from ASTM, or it may be obtained commercially.



TEST ASSEMBLY

PERFORMANCE PROPERTY: ENVIRONMENTAL STRESS RUPTURE
REFERENCED TEST METHOD: ASTM D2552
ALTERNATIVE METHODS: ---
SCOPE: POLYETHYLENE GEOMEMBRANES
TARGET VALUE: TIME TO SPECIMEN RUPTURE
UNITS: hours

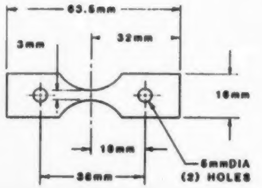
SUMMARY OF METHOD

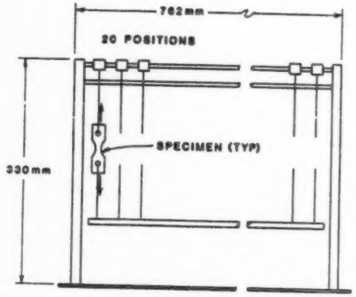
The referenced test method covers the determination of the susceptibility of polyethylene to stress rupture under specified conditons. The test is generally used to rank the Performace of polyethlyenes under a constant tensile load in the presence of a surface agent at a specified test temperature. Like environmental stress cracking, environmental stress rupture is dependent on test environment, loading and speciment stress history. Results obtained do not necessarily relate to the field performance of the geomembrane.

Twenty specimens are cut to the shape shown below. The thickness is measured and the minimum cross-sectional area of each specimen is calculated. The test load for each specimen is selected based on the constant test stress selected by the user. The test bath is filled with a surface active agent, e.g., Igepal CO-630 and the temperature of the bath is set to 50°C. Specimens are attached to the test frame, and immersed in the test bath. Each specimen is then loaded and the elapsed time to failure is recorded. The type of failure (brittle or ductile) is recorded - brittle failures are preferred. The failure time for each specimen is plotted on semi-log paper versus the specimen plotting position. The best fit straight line through the data points is used to determine the F_{50} value, that is the probable time required for 50% of the speciments to fail in a brittle mode. The F_{50} value is reported. The tests can be run on the parent material or on the seams.

TEST EQUIPMENT

Specimen cutting die, stress rupture apparatus, surface agent, and constant temperature bath are commercially available.





INDEX PROPERTY: PEEL ADHESION OF GEOMEMBRANE SEAMS
REFERENCED TEST METHOD: ASTM D413 (modified)
ALTERNATIVE METHODS: ASTM D816 Method C (Rubber)
ASTM D751 (Reinforced Geomembrane)
SCOPE: GEOMEMBRANE SEAMS
TARGET VALUE: PEEL STRENGTH
UNITS: N/m (lbf/in)

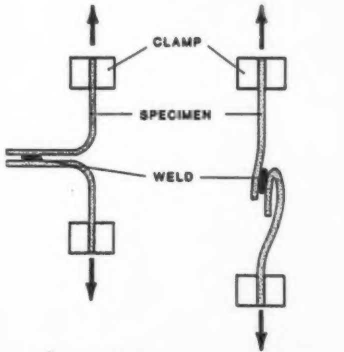
SUMMARY OF METHOD:

The "peel" test is performed on test specimens removed from a sample of factory or field geomembrane seams or "welds" for quality control purposes. In addition, the ply adhesion of composite materials can be tested using this method. The test can be performed in the field or the lab.

A rectangular specimen, usually 25 to 50 mm (1-2") wide is carefully cut from the test sample. Opposing edges of the seam specimen are placed into grips of a Constant-Rate-of-Extension (CRE) tensile testing device (see figure). A 90° or 180° peel test can be performed, with the latter most suited for very flexible parent sheet material. The specimen is tested to failure at a rate of 50 to 150 mm/min (2" to 6"/min). The maximum force is recorded. The specimen is carefully observed to identify the mode of failure (peel failure of weld, tearing of sheet material, etc.). Traditionally, the geomembrane industry has interpreted the results of this test in a qualitative manner using the film tear bond (FTB) criteria. The test is used as an indicator that the apparent strength of the bond is greater than the strength of the parent material. This is a visual determination often used as a basis of qualifying field welds. The recorded adhesion force can be used as a check on specimen variability.

TEST EQUIPMENT:

CRE Tensile Testing Device.
Specimen cutting die.



90° PEEL TEST

180° PEEL TEST

INDEX PROPERTY: GRAB TENSILE STRENGTH
REFERENCED TEST METHOD: ASTM D4632
ALTERNATIVE METHODS: ASTM D1682 (modified), ISO 5032-1982(E)
SCOPE: GEOTEXTILES (except for knitted)
TARGET VALUE: BREAKING LOAD
UNITS: N (lbf)

SUMMARY OF METHOD:

The Grab Tensile Strength test described is suitable for quality control testing during manufacture or for commercial acceptance testing. There is no known correlation between grab tensile strength and strength values obtained using strip methods.

The grab tensile test is a uniaxial test where the specimen is wider than the test clamps. The tensile strength added by the unclamped portion of the specimen is influenced primarily by geotextile construction. Testing of knitted geotextiles using this method is not recommended. Because of the geometry of the test and contribution of unclamped areas a simple relationship between load and elongation cannot be expressed, so the term "apparent elongation: is used.

A 100x200 mm (4x8") specimen is placed centrally in a set of parallel 25x50 mm (1"x2") clamps such that the clamps are spaced 75 mm (3") apart. Care should be exercised to insure that the long dimension of the clamps are parallel to the direction of loading. A pretension of 0.5% of the breaking load is applied if apparent elongation is to be measured. Apparent elongation is measured at the cross-head. A CRE tensile testing device is operated at a rate of 300 mm/min (12"/min) until rupture of the specimen. Ten specimens are tested in each of the principal directions and results in each direction are averaged and presented separately. The breaking load is the maximum load applied to the specimen. The grab strength has units of force, although the unit of force per unit width of the jaws is implied. It is important to note the jaw width (25 mm or 1") when considering grab tensile strength data.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) tensile testing device, flat clamps as described above.

INDEX PROPERTY: STRIP TENSILE STRENGTH
REFERENCED TEST METHOD: ASTM D1682
ALTERNATIVE METHODS:
SCOPE: GEOTEXTILES
TARGET VALUE: BREAKING LOAD
UNITS: N/m (lbf/in)

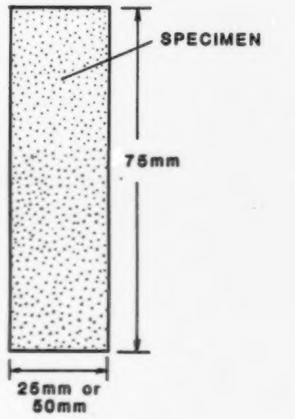
SUMMARY OF METHOD:

The strip tensile test is a uniaxial test where a 25 mm (1") or 50 mm (2") wide strip of geotextile is extended between two clamps moving in a direction parallel to the direction of loading until failure of the specimen occurs. The test generates a load-elongation curve and is suitable for quality control or comparison testing of geotextiles. Due to the high transverse strains ("necking") which accompany testing of some types of geotextiles, this test method is not recommended for use as a design aid.

The 75 mm (3-in. long) specimen may be tested in the wet or dry condition. A pretension of up to 0.5% of the maximum load can be applied to the specimen. The ultimate force required to rupture the specimen is the tensile strength of the specimen.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) Tensile Testing Device.



INDEX PROPERTY: HYDROSTATIC BURSTING STRENGTH
REFERENCED TEST METHOD: ASTM D751 (Diaphragm)
ALTERNATIVE METHODS: ASTM D3786
DIN 53861
SCOPE: GEOTEXTILES, SOME GEOMEMBRANES
TARGET VALUE: BURSTING STRENGTH
UNITS: kPa (psi)

SUMMARY OF METHOD:

The referenced test method was developed for testing coated fabrics which have a relatively low elongation at failure. Geomembranes having relatively low elongations at failure, such as reinforced membranes, may also be tested using this method. Testing of high elongation rubber or thermoplastic specimens is not be limited for use in the diaphragm burst testing device described.

The diaphragm bursting tester can be operated either hydraulically or pneumatically. Two circular steel disks with a 75 mm (3") outer diameter and openings of 31 mm (1.25") clamp the specimen horizontally over a membrane. The membrane is expanded under a constantly increasing pressure until rupture of the specimen occurs. The bursting strength is the corrected gross pressure recorded, and is reported as an average of ten specimens.

TEST EQUIPMENT:

Diaphragm Burst Tester (as described in test method).

INDEX PROPERTY: TEARING STRENGTH
REFERENCED TEST METHOD: ASTM D4533 (TRAPEZOID TEAR)
ALTERNATIVE METHODS: DIN 53859/2 (TONGUE TEAR)
SCOPE: GEOTEXTILES
TARGET VALUE: TEARING STRENGTH
UNITS: N (lbf)

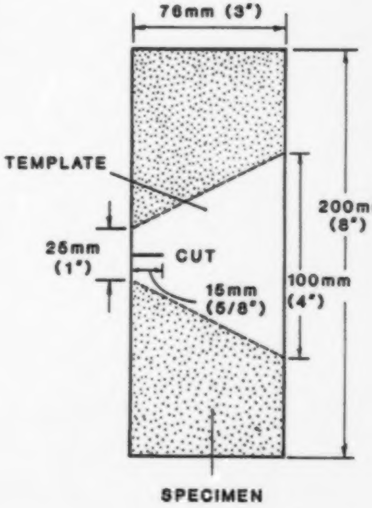
SUMMARY OF METHOD:

The trapezoid-type tear test described measures the force required to propagate a tear in the test specimen. This tear resistance is a function of yarn or fiber type and geotextile construction. Tear strength is measured and reported for each of the principal geotextile directions.

On a rectangular specimen measuring 76 mm by 200 mm (3"x8"), a trapezoid is marked, as shown below. A 15 mm (5/8") cut is made perpendicular to the specimen edge in the center of the short (25 mm or 1") side of the trapezoid. The specimen is gripped in flat clamps extending the entire width of the nonparallel edges of the trapezoid. The clamps are placed in a Constant-Rate-of-Extension (CRE) tensile testing device, which operates at a rate of 300 mm/min (12"/min). The total force is measured as a function of jaw extension, and the tearing strength is the maximum force recorded. If multiple peaks are observed on the force vs. elongation plot, the tearing strength is the value of the highest peak. A total of 10 specimens are tested in each principal direction unless the coefficient of variation of the geotextile tested is known.

TEST EQUIPMENT:

CRE tensile testing device, flat clamps.



INDEX PROPERTY: ABRASION RESISTANCE
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ASTM D1175
SCOPE: GEOMEMBRANES, GEOTEXTILES
TARGET VALUE: TENSILE STRENGTH LOSS
UNITS: %

SUMMARY OF METHOD:

The referenced test method covers the abrasion resistance of a specimen using the sand paper sliding block method. Like other abrasion tests, such as test methods using rotating wheels or drums, this is an index test method suitable for comparison, within some limitations, of candidate geomembranes or geotextiles. Because the ultimate utility of this procedure in geosynthetics has not been determined, and because the relationship between laboratory tests and field performance is not known, the abrasion test is not recommended for use in design.

The sand paper-sliding block method involves a specimen being abraded using a reciprocal action under some combination of normal pressure, abrading cycles and abrading surfaces. Rectangular specimens measuring 75 x 200 mm (3"x8") are clamped onto a stationary upper plate in the test device. The abrading medium is placed on the lower reciprocating plate. The upper plate is released so that the specimen and abrading medium are in uniform contact. The top plate is loaded with a specific weight, and the specimen is abraded using a stroke of 25 mm (1") at a specific speed and number of cycles. In the absence of other material specifications, the abrading medium is 100 grit Emory cloth. The normal load is 1 kg, the speed is 30 cycles/minute and the test duration is 250 cycles, or rupture of the specimen. The percentage of strength loss is determined by testing a set of control and abraded specimens using the 2-in. raveled strip or cut strip method (ASTM 1682 modified). Five specimens tested each in the machine and cross machine direction are tested, and the average loss of breaking strength is reported. The test may also be run to rupture of the specimens. In this case, the average number of cycles to failure for five specimens is reported.

TEST EQUIPMENT:

Balanced head and block assembly, cycle counter, weights, abrading medium and Constant-Rate-of-Extension (CRE) Tensile Testing Device. Details on the head and block assembly are not yet available.

INDEX PROPERTY: MAXIMUM PORE (OPENING) SIZE
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: USA CORPS OF ENGINEERS CW02215
SCOPE: GEOTEXTILES
TARGET VALUE: APPARENT OPENING SIZE (AOS)
UNITS: mm

SUMMARY OF METHOD:

The test method referenced is one of the sieving-type methods to determine the apparent (equivalent) opening size of a geotextile specimen. This type of procedure generates data that is misleading for some nonwoven geotextiles, and is often difficult to interpret. Although the test is intended as an index test, the opening size data is being used as a part of geotextile design in filtration or separation applications because there is no widespread accepted alternative at this time. Caution in interpretation of the results is advised since the precision and interlab bias of the method has not been established.

The method involves placing a geotextile specimen without tension into a sieve frame between two sieves. Uniform spherical glass beads, starting with the smallest diameter beads, are placed on the geotextile specimen, and the frame is shaken for ten minutes. The beads that fall through the specimen are weighed and expressed as the percent of the glass beads passing through the specimen. The procedure is repeated for the same specimen using successively larger beads. Trials are repeated until the percent of beads passing through the specimen is 5% or less. Five specimens are tested in this manner. The apparent opening size (AOS or O95) is defined as the bead diameter value, in mm, that intersects the 5% passing mark. The AOS can also be expressed as a US standard sieve number for the next larger size sieve or mesh.

TEST EQUIPMENT:

Sieve shaker, 200 mm (8") diameter sieves, pan and cover. Commercially available glass beads and anti-static devices. Sources of beads and anti-static devices will be published with the test method.

INDEX PROPERTY: DEGRADATION FROM EXPOSURE TO ULTRAVIOLET LIGHT
REFERENCED TEST METHOD: ASTM D4355
ALTERNATIVE METHODS: ---
SCOPE: GEOTEXTILES
TARGET VALUE: PERCENT OF TENSILE STRENGTH RETAINED
UNITS: % or N/m (lbf/in)

SUMMARY OF METHOD:

The behavior of a geosynthetic specimen exposed to ultraviolet radiation is compared to that of a control specimen. Exposure consists of 120-minute cycles consisting of 102 minutes of light followed by 18 minutes of water spray and light within a Xenon-Arc Apparatus. Five specimens are tested for each exposure time (150,300 and 500 hr UV exposure) for each of the principal directions, and are compared to five unexposed control specimens. The specimens are compared by testing for tensile strength using a 2-in. wide strip specimen (ASTM D1682 Method D). The percent loss of strength of the exposed specimens is calculated for each exposure time. Results can be expressed as a plot of percent of breaking strength lost (or retained) versus exposure time.

The Xenon-Arc type exposure cannot simulate all the variables of ultraviolet radiation contained in sunlight. Test results may have no direct correlation to actual sunlight exposure.

TEST EQUIPMENT:

Xenon-Arc Apparatus Type BH or Type C, as described in ASTM G-26, CRE tensile testing device outlined in ASTM D1682.

INDEX PROPERTY: TEMPERATURE STABILITY
REFERENCED TEST METHOD: ASTM D4594
ALTERNATIVE METHODS: ---
SCOPE: GEOTEXTILES (except knitted)
TARGET VALUE: CHANGE IN BREAKING STRENGTH AND ELONGATION
UNITS: %

SUMMARY OF METHOD:

The referenced test method is used as an index test to compare the change in breaking strength and elongation of different geotextile specimens under controlled chnages in temperature. Freeze-thaw, elevated or low temperature conditions can be examined, and the relative effects of these conditions on different geotextiles compared. The 2" cut or ravel strip tensile test (ASTM D1682 modified) is used as the referee method for determining breaking strength and elongation. The test is performed using a Constant-Rate-of-Extension (CRE) device inside an environmental chamber capable of maintaining temperature from 040°C to 100°C (-40°F to 212°F). Five geotextile specimens in the machine and cross machine directions are prepared as control specimens and for testing within the environmental chamber. After the specimen is inserted into the jaws of the CRE device, the temperature of the chamber is set. If desired, a specified number of freeze-thaw cycles may be applied to the specimen prior to testing. The tensile test is performed at the specified test temperature and the specimen is tested to failure as directed in ASTM D1682. The average specimen breaking load and elongation at failure is compared to those of the control specimens. Results are reported as the average percent change in breaking load and elongation under the specific conditions tested.

TEST EQUIPMENT:

CRE tensile testing device, environmental chamber with temperature regulation and measurement equipment.

INDEX PROPERTY: WATER PERMEABILITY (PERMITTIVITY)
REFERENCED TEST METHOD: ASTM D4491
ALTERNATIVE METHODS: France: CFGG NF G38-016
Other European
SCOPE: GEOTEXTILES
TARGET VALUE: WATER PERMITTIVITY
UNITS: sec^{-1}

SUMMARY OF METHODS:

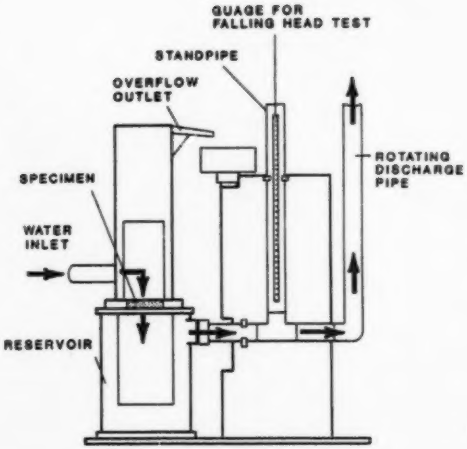
This standard describes test methods for both constant head and falling head techniques.

Constant Head Test - A constant head of 50 mm (2") is maintained over the 73 mm (2.87") diameter specimen. Flow quantity versus time is recorded. Desired water (dissolved oxygen content - 6 ppm) is recommended for use in this test. The permittivity is determined from the average of 5 flow rate readings per specimen. The permittivity value for the specimen is considered valid only within the laminar flow regime. The test method includes provision for determining the limits of the laminar flow regime by running the test at various heads. All values are corrected for temperature.

Falling Head Test - A falling head over a range from 80 mm (3.25") to 20 mm (0.75") is used to determine permittivity of geotextile specimens using the same device and conditions as the constant head technique. The time for the water level to drop the required distance is recorded and averaged for at least 5 trials per specimen. All values are corrected for temperature.

TEST EQUIPMENT:

Detailed drawings and materials list available from ASTM.



PERFORMANCE PROPERTY: COMPRESSIBILITY/CRUSH STRENGTH
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ---
SCOPE: ALL GEOSYNTHETICS
TARGET VALUE: DEFORMATION UNDER LOAD OR CRUSH STRENGTH
UNITS: kPa (psf)

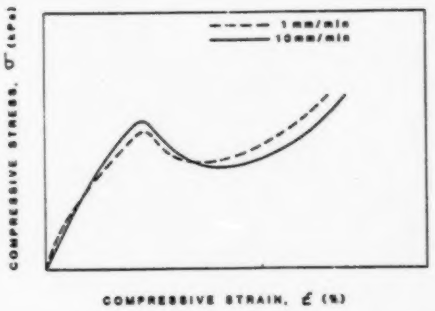
SUMMARY OF METHOD:

The referenced draft method covers the determination of the compressive stress-strain characteristics of geosynthetics. The crush strength can be evaluated for some geosynthetics. The test is intended as an index test, but some data generated can be used for design purposes, for instance, the selection of compressive stress levels for use in compressive creep testing. Since the compressibility of a geosynthetic specimen may be highly time-dependent, the use of this method alone to predict long term behavior of geosynthetics is not recommended.

The specimens are at least 100 mm (4 in) square. Geocomposite or geonet specimens are trimmed to preserve structural capacity. The specimen is placed between 2 flat rigid platens, and a seating load of 2 kPa (42 psf) is applied. Compressive loads are then applied at a constant rate of deformation of 1 mm/min. Deformation and load are recorded simultaneously for at least 20 distinct data points and the data is plotted on a stress-strain curve similar to the one shown below. The test is repeated on another specimen at a deformation rate of 10 mm/min. The crush strength and the compressive modulus may be determined from the stress-strain plot.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) Testing Device, load platens and load and deformation monitoring devices.



APPENDIX D - PERFORMANCE PROPERTIES

I GEOMEMBRANES

PAGE

Chemical Resistance, EPA 90/90 DI-1
Bonded Shear Strength (Shear), ASTM D751 DI-2
Bonded Shear Strength (Shear), ASTM D816 DI-3
Bonded Shear Strength (Shear), ASTM D882 DI-4
Hydrostatic Bursting Resistance, DI-5
Nondestructive Seam Evaluation - Ultrasonic Shadow Method - GRI# GM1-86 DI-6
Nondestructive Seam Evaluation - Ultrasonic Pulse Echo Technique - ASTM D4437 DI-7
Nondestructive Seam Evaluation - Vacuum Box Technique - ASTM D4437 DI-8
Nondestructive Seam Evaluation - Pressure Testing Technique DI-9
Nondestructive Seam Evaluation - Air Lance Technique, ASTM D4437 DI-10
Embedment Depth for Anchorage Mobilization GRI# GM2 - 87 DI-11

II GEOTEXTILES

Breaking Strength - Wide Width Strip Method, ASTM D4595 DII-12
Sewn Seam Strength - Proposed ASTM DII-13
Coefficient of Soil/Geosynthetic Friction, Proposed ASTM DII-14
Puncture Strength (CBR), DIN 54307 DII-15
In-Plane Flow (Transmissivity), ASTM D4617 DII-16
Water Permeability Under Stress, Proposed ASTM DII-17
Clogging Potential (Gradient Ratio Method), Proposed ASTM DII-18
Long Term Flow Rate (Clogging), GRI# GT 1-86 DII-19

III GEONETS/GEOCOMPOSITES

Tensile Creep, Proposed ASTM DIII-20
Compressive Creep, GRI# GS 4-87 DIII-21
Flow Channel Intrusion, GRI# GC 3-87 DIII-22
Bond Strength/Adhesion, ASTM F904 DIII-23

DI-1

PERFORMANCE PROPERTY: CHEMICAL RESISTANCE
REFERENCED TEST METHOD: EPA 90/90 (Draft)
ALTERNATIVE METHODS: ASTM PROPOSED (Geotextiles)
ASTM D543 (Geomembranes)
SCOPE: GEOSYNTHETICS
TARGET VALUE: CHANGE IN PHYSICAL AND MECHANICAL PROPERTIES
UNITS: %

SUMMARY OF METHOD:

The draft EPA method referenced is the most commonly used chemical resistance or compatibility test at this time. It is intended as a means of comparing different types of geomembranes (to identify incompatible ones) or to provide the user with an indication of geomembrane behavior when exposed to certain chemicals or leachates. Extrapolation of such behavior over the design life of the application (often 50 years or longer) is required.

This accelerated test involves complete immersion of the specimens in a "representative" sample of leachate or other chemical expected to be present in the geomembrane field environment. The testing period is currently 120 days, although this period may be extended to 180 days or more in the final draft. Tests are conducted at temperatures of 23 and 50°C (73 and 122°F). A series of control (unexposed) tests are run, and duplicate tests are run after exposure times of 30, 60, 90 and 120 days, althoguh more frequest testing may be performed. The tests performed include: specimen mass per unit area and dimensional stability, thickness, environmental stress cracking (crystalline or semicrystalline specimens), tear, puncture, tensile strength and elongation, hydrostatic resistance (except for rubbers), volatiles, extractables (except for scrim reinforced) and ply adhesion (for scrim reinforced specimens or seams). Creep-type properties and other performance properties are not currently addressed. The percent change in the physical and mechanical properties as compared to control specimens is plotted against immersion time. The trend of the data provides an indication of the compatibility of the geomembrane specimen and waste fluid.

TEST EQUIPMENT:

Suitable waste containers, temperature monitoring and control device, oven, waste fluid monitoring and circulating equipment, analytical balance and all apparatus required for performing desired physical, chemical and mechanical properties tests.

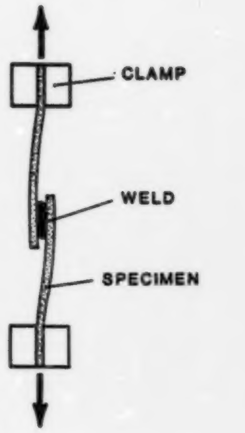
PERFORMANCE PROPERTY: BONDED SEAM STRENGTH (Shear)
REFERENCED TEST METHOD: ASTM D751
ALTERNATIVE METHODS: ---
SCOPE: SCRIM REINFORCED GEOMEMBRANES
TARGET VALUE: BONDED SEAM BREAKING LOAD
UNITS: kN/m (lbf/in)

SUMMARY OF METHOD:

The scope of the referenced test method is limited to bonded seam strength of scrim-reinforced geomembranes and some composites. The method is a modified grab method (ASTM D1682). Jaws for this method measure 25x75 mm (1"x3"). The specimen is 50x200 mm (2"x8") with the bonded seam in the center of the long dimension of the specimen. The free ends of the specimen extend parallel in opposite directions to allow clamping. The specimen is loaded in tension in a direction perpendicular to the seam at a rates of either 5 mm/s (12"/min) or 0.85 mm/sec (2"/min). The maximum load (kN/m or lbf/in) before rupture of the specimen is the bonded shear strength. The location of the observed rupture for each specimen is recorded. A minimum of three specimens are tested.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) Tensile Testing Device, flat clamps.



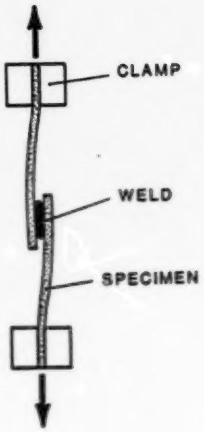
PERFORMANCE PROPERTY: BONDED SEAM STRENGTH (SHEAR)
REFERENCED TEST METHOD: ASTM D816 Method B
ALTERNATIVE METHODS: ---
SCOPE: RUBBER GEOMEMBRANES
TARGET VALUE: BONDED SEAM BREAKING LOAD
UNITS: kN/m (lbf/in)

SUMMARY OF METHOD:

The referenced test method was developed for testing rubber adhesives. Method B is used to measure the adhesion in shear of a bonded seam strip specimen measuring 25 mm (1") in the absence of any seam specification. A lap seam in the central portion of the specimen is tested with the free ends of the specimen parallel to and on opposite sides of the seam for clamping. The entire specimen width is clamped. The bonded area is kept parallel to the direction of testing by using shims at the jaw locations. This is to reduce the peel component in the failure of the specimen. The test is conducted at a strain rate of 0.8 mm/s (2"/min) and the maximum load applied to the specimen is recorded. The shear adhesion is reported as the average load per unit width (kN/m or lbf/in) for six specimens.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) Tensile Testing Device, suitable clamps, specimen cutting dye (optional).



PERFORMANCE PROPERTY: BONDED SEAM STRENGTH (SHEAR)
REFERENCED TEST METHOD: ASTM D882 (modified)
ALTERNATIVE METHODS: ASTM D638 (Dumbbell-shaped specimens)
SCOPE: GEOMEMBRANES (except scrim reinforced)
TARGET VALUE: BONDED SEAM BREAKING LOAD
UNITS: kN/m (lbf/in)

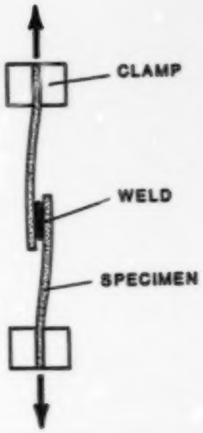
SUMMARY OF METHOD:

The referenced test method is the preferred method for testing for tensile or seam strength properties of thin (less than 1 mm, or 40 mil in thickness) plastic nonreinforced geomembranes. ASTM D638 is the preferred method for testing plastics greater than 1 mm (40 mil) in thickness. For quality control testing of seams, modifications of ASTM D882 are generally used. The specimen is 25 mm (1") wide and the length of the specimen is 100 mm (4") plus the width of the seam. As in all tensile tests on plastics, the specimen must be cut out carefully to avoid stress concentrations. Cutting dies are required to make all specimens as uniform as possible.

The test specimen is gripped along its entire width and tested to failure at a uniform rate of 8 mm/s (20"/min). The ultimate load per unit width of the specimen is the bonded seam breaking load in kN/m (lbf/in). Each specimen is carefully observed and the mode and location of failure are reported for each specimen. A visual qualification/disqualification criteria, known as the film tear bond (FTB), is often reported for each specimen instead of the bonded seam breaking load.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) tensile testing device, clamps, specimen cutting die, and measuring devices.



PERFORMANCE PROPERTY: HYDROSTATIC BURSTING RESISTANCE
REFERENCED TEST METHOD: ---
ALTERNATIVE METHODS: DREXEL UNIVERSITY GRI #GM3-87
SCOPE: GEOMEMBRANES
TARGET VALUE: BURSTING RESISTANCE
UNITS: % Strain, Number of days at prescribed pressure

SUMMARY OF METHOD:

The performance hydrostatic bursting resistance test apparatus described is based on devices fabricated by the US Bureau of Reclamation and other organizations in the US and Europe. The device consists of a large cylindrical split chamber measuring as large as 60 to 90 cm (2 to 3 ft.) in diameter. A geomembrane specimen is supported on flanges at the chamber split. The lower chamber can be filled with soil or other test media. The upper chamber may be filled with water and air pressure applied. The device may be operated as a large burst tester if the specimen is tested to failure. Performance properties of a candidate geomembrane can be examined under simulated field conditions. The effect of soil density, surface uniformity, etc., can be examined under particular stress conditions. The effects of friction, rutting of a soil subgrade (from equipment or subsidence), dessication cracking, or the effects of a geotextile substrate can be examined. Stress-strain measurements can be made so that the limiting geomembrane strain for field conditions can be approximated. Long-term hydrostatic resistance tests can be conducted to investigate performance, or even creep behavior of a geomembrane. No standard test method currently exists, but an ASTM subcommittee has recommended that this test method be reviewed and considered for performance testing.

TEST EQUIPMENT:

Large diameter pressure chamber; must be custom fabricated.

PERFORMANCE PROPERTY: NONDESTRUCTIVE SEAM EVALUATION - ULTRASONIC SHADOW METHOD
REFERENCED TEST METHOD: DREXEL UNIVERSITY GRI #GM1-86
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANE SEAMS
TARGET VALUE: RELATIVE SEAM SOUND ENERGY TRANSMISSION
UNITS: % of Calibrated Standard Maximum

SUMMARY OF METHOD:

The referenced test method covers the evaluation of field or factory seams using the Ultrasonic Shadow Method technique. The method is suitable for all types of solvent, taped, thermal (including extruded), and combination seams. An indication of the quality of field seams is recorded and compared to competent control seams. The presence of unbonded sections, voids, foreign objects, and nonhomogenities can be detected. This technique can be used to assist in the selection of locations for destructive tests. The Shadow Method apparatus consists of a high frequency pulse generator (~1MHZ), transducers, and a CRT display. The pulse is sent into the upper geomembrane on one side of the seam and is received on the lower geomembrane on the opposite side of the seam. Roller mounted transducers or soft rubber coupling tips can be used. The system is first calibrated on unseamed parent material and then on a control section of seam known to be competent. The signal signature is observed on the CRT for the control seam and the amplitude is adjusted to full screen height (FSH). An alarm is set for any amplitude received less than some minimum allowable threshold amplitude. The threshold value is set in specifications and is generally in the 15-25% FSH range. For testing, the seam is wiped clean with a clean dry cloth after suitable curing period of the seam. The transducers are placed so that the seamed area(s) is straddled. The technician pushes the transducer assembly and the amplitude signature is indicated on the CRT which is transported with the assembly. A maximum testing rate of about 2 m/min (6 linear ft. per minute) of seam can be attained.

TEST EQUIPMENT:

The ultrasonic shadow system is commercially available.

PERFORMANCE PROPERTY: NONDESTRUCTIVE SEAM EVALUATION - ULTRASONIC PULSE ECHO TECHNIQUE
REFERENCED STANDARD PRACTICE: ASTM D4437
ALTERNATIVE METHODS: ---
SCOPE: MOST UNREINFORCED GEOMEMBRANE SEAMS
TARGET VALUE: INDICATION OF UNBONDED AREA
UNITS: Abatement of Pulse Energy

SUMMARY OF METHOD:

The referenced standard practice lists several destructive and nondestructive seam evaluation techniques, including the ultrasonic pulse echo technique for most nonreinforced field seams. A high frequency (1-15 MHZ) sound wave passes through the seam overlap. A continuous seam will allow a return of the sound energy to the single transducer unit, which is connected to a monitor. Discontinuities in the seam result in an abatement of the pulse energy below some threshold energy which triggers an alarm on the device.

Continuous surface contact between the transducer and the seam must be maintained and water couplant is required. For this reason, this technique is limited for use on some extruded seams and extremely time consuming for double welded seams. This technique can be used to detect discontinuities, foreign matter, etc., but gives only an empirical indication of seam quality. The use of this method in conjunction with a destructive technique is recommended.

TEST EQUIPMENT:

Ultrasonic pulse echo equipment is commercially available.

PERFORMANCE PROPERTY: NONDESTRUCTIVE SEAM EVALUATION - VACUUM BOX TECHNIQUE
REFERENCED STANDARD PRACTICE: ASTM D4437
ALTERNATIVE METHODS: ---
SCOPE: MOST GEOMEMBRANE SEAMS
TARGET VALUE: INDICATION OF UNBONDED AREA
UNITS: Visual

SUMMARY OF METHOD:

The referenced standard practice lists several destructive and nondestructive seam evaluation techniques, including the use of a vacuum box. The vacuum box provides visual evidence of unbonded areas or continuous voids across the seam. The permeability of the seam in the unloaded (unstressed) condition is examined, but the mechanical strength of the seam is not addressed.

The vacuum box consists of a metal box with a clear glass top and a soft rubber gasket around the perimeter of the open bottom. The seam is cleaned and a soap solution is applied to the seam area. The box is placed over the seam and the entire gasket compressed to seal against the liner. A vacuum is applied and maintained inside the box. In areas where disbonds or voids exist, soap bubbles are generated and are observed inside the box. These areas are marked for repair.

This method is commonly used at the present time for field quality control of geomembrane seams. The vacuum technique has several limitations including use around penetrations and on some extruded seams. The use of the vacuum box testing is recommended only in conjunction with full-time observation and other testing methods (destructive and/or nondestructive).

TEST EQUIPMENT:

Generator, vacuum pump and vacuum box are commercially available.

PERFORMANCE PROPERTY: NONDESTRUCTIVE SEAM EVALUATION - PRESSURE TESTING TECHNIQUE
REFERENCED TEST METHOD: ---
ALTERNATIVE METHODS: ---
SCOPE: DUAL THERMALLY FUSED GEOMEMBRANE SEAMS WITH AIR GAP (nonreinforced)
TARGET VALUE: INDICATION OF UNBONDED AREA
UNITS: Loss of Air Pressure

SUMMARY OF METHOD:

The pressure testing technique is suited for testing dual thermally fused seams in relatively rigid material, such as polyethylene. The commercial technique is patented and is performed by licensed installers.

Two parallel seams are made with a small air gap between, resulting in a continuous air channel along the entire length of the seam. The air channel is sealed at the ends and is inflated to a specific air pressure for a specific time period. Channel pressure of 210 kPa (30 psi) and a period of 30 minutes are typical. A loss of pressure (after allowances for expansion of the geomembrane) indicates an unacceptable seam. The leak can be located by systematically halving the test area and retesting.

This technique can provide an indication of the mechanical strength and the watertightness of both of the dual seams. The use of the pressure technique is limited in patch areas or penetrations where dual welds are not usually constructed.

TEST EQUIPMENT:

Air pump, pressure indicator, and miscellaneous sealing and patching equipment.

PERFORMANCE PROPERTY: NONDESTRUCTIVE SEAM EVALUATION - AIR LANCE TECHNIQUE
REFERENCED STANDARD PRACTICE: ASTM D4437
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANE SEAMS (Flexible Geomembranes)
TARGET VALUE: INDICATION OF UNBONDED AREA
UNITS: Visual

SUMMARY OF METHOD:

The referenced standard practice lists several destructive and nondestructive seam evaluation techniques, including the air lance test. The air lance test provides visual evidence of completely unbonded seam areas in very flexible geomembranes. An air nozzle is held a maximum of 50 mm (2") from the seam edge and air at 345 kPa (50 psi) pressure is directed toward the seam. The unbonded seam areas are observed visually. This technique is severely limited and does not provide an indication of seam strength or water tightness. Only large, completely unbonded areas can be detected using the air lance. With proper welding techniques and quality control, and the use of other testing methods, this technique is not necessary and is not recommended.

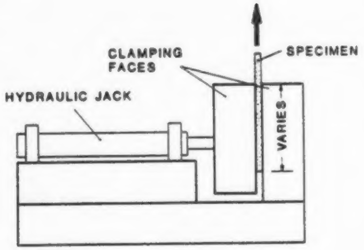
PERFORMANCE PROPERTY: EMBEDMENT DEPTH FOR ANCHORAGE MOBILIZATION
REFERENCED TEST METHOD: DREXEL UNIVERSITY GRI #GM2-87
ALTERNATIVE METHODS: ---
SCOPE: GEOMEMBRANES, GEOCOMPOSITES
TARGET VALUE: EMBEDMENT DEPTH
UNITS: cm (in.)

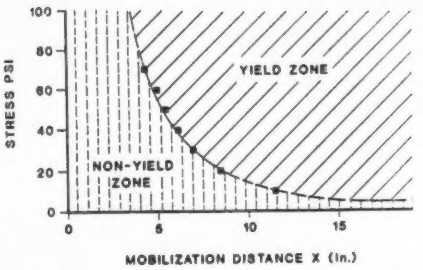
SUMMARY OF METHOD:

Required in many design procedures for geomembranes and geocomposites is the embedment depth necessary to mobilize a certain stress level. For polyethylene, this stress level is the yield stress. For geomembranes other than polyethylene, the stress level will be that required to reach a certain strain, e.g., 100%. The specimens are 150 mm (6") wide and of variable length. The specimen length is placed between steel plates faced with sandpaper as shown in the sketch. Normal pressure is applied to the steel plates and the free end of the specimen is tensioned using a Constant-Rate-of-Extension (CRE) tensile testing device. The embedment depth at which the targeted stress level is based on a series of trials as shown in the figure below. Normal pressures of 25 to 500 kPa (500 to 10,000 lb/ft^2) can be applied resulting in required embedment depths of 25 to 300 mm (1" to 12").

TEST EQUIPMENT:

CRE tensile testing device and custom fabricated jaws and assembly. Sketches of jaws and assembly will be available through GRI.





EXAMPLE: STRESS vs MOBILIZATION DISTANCE FOR HDPE

PERFORMANCE PROPERTY: BREAKING STRENGTH - WIDE WIDTH STRIP METHOD
REFERENCED TEST METHOD: ASTM D4595
ALTERNATIVE METHODS: ---
SCOPE: GEOTEXTILES, GEOGRIDS
TARGET VALUE: TENSILE STRENGTH AND ELONGATION
UNITS: N/m (lbf/in), %

SUMMARY OF METHOD:

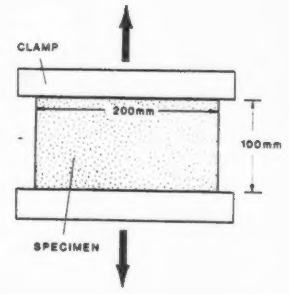
The wide width strip method utilizes a specimen having a width of 200 mm (8") and a gauge length of 100 mm (4"). This reduces the effect of high transverse strains, or "neckdown" common in the narrow strip or grab methods. It is widely believed that this produces results more closely related to anticipated field behavior.

The specimen is gripped along its entire width in the clamps of a Constant-Rate-of-Extension (CRE) type tensile testing device operated at a constant strain rate of 10%/min. Force and elongation are continuously monitored as the specimen is tested to rupture. A minimum of six specimens in each of the principle geosynthetic directions is recommended. The specimen is discarded if slippage of the specimen from the clamps occurs during testing or if the specimen breaks at or near the jaws. Limitations of the jaws and the need to modify the jaw face under certain conditions is addressed.

The tensile strength, elongation and initial and secant tensile moduli may be calculated for each specimen. Construction of the load - elongation curve and initial and secant moduli is illustrated in the appendix of the standard. Modifications of this procedure are being considered for use with geomembrane specimens.

TEST EQUIPMENT:

CRE tensile testing device, force and elongation measuring devices, and clamps as described in standard. Illustrations of alternative clamps are included. Roller clamps, although not addressed in the standard, have been shown to be effective for high strength woven geotextiles.



PERFORMANCE PROPERTY: SEWN SEAM STRENGTH
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ASTM D1682 (modified)
SCOPE: GEOTEXTILES, GEOMEMBRANES, SOME COMPOSITES
TARGET VALUE: SEAM BREAKING LOAD
UNITS: kN/m (lbf/in)

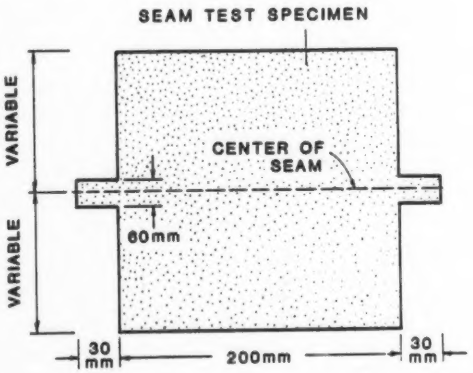
SUMMARY OF METHOD:

The referenced test method uses the wide strip method (ASTM D4595) as its basis. The sewn seam specimens are 200 mm (8") wide with the sewn seam centrally located. A "blockout of 30 mm (1.25") is left on either side of the seam along the center of the specimen as illustrated on the figure below. The specimen is failed in tension in a direction perpendicular to the seam. The test method is intended for acceptance testing of sewn seams, and is best suited for testing of sewn geotextile seams. The suitability of testing sewn seams or combination sewn-bonded seams for geomembranes or composites using this test method has not been determined. Modified grab methods may be considered. Narrow strip-type specimens may not yield reproducible results.

For the wide strip method, a minimum of six seam specimens are tested and the average is reported as the average peak load applied to the specimen, in units of kN/m (lbf/in). For multiple stitch seams or combination seams, multiple peaks may be reported.

TEST EQUIPMENT:

Constant-Rate-of-Extension Tensile Testing Device (CRE), specimen clamps, as described in ASTM D4595, or roller clamps, and a specimen cutting template (optional).



PERFORMANCE PROPERTY: COEFFICIENT OF SOIL/GEOSYNTHETIC FRICTION
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ---
SCOPE: GEOSYNTHETICS
TARGET VALUE: COEFFICIENT OF FRICTION
UNITS: DIMENSIONLESS

SUMMARY OF METHOD:

The test method referenced covers the determination of the coefficient of soil/geosynthetic friction by the direct shear method. The procedure, which is similar to that used for testing of soils, can also be used to determine the coefficient of geosynthetic/geosynthetic friction. When testing the geosynthetic specimens alone, the test functions as an index test. Because of the variability of the soils and conditions tested and the presence of several possible failure mechanisms, soil/geosynthetic friction tests are intended to produce design data.

The direct shear apparatus proposed is square or rectangular with a minimum width of 300 mm (12") and depth of 50 mm (2"). A shear force is applied to a traveling container while a normal compressive stress is applied to the overlying stationary container. The soil is placed into each container as specified by the user. The geosynthetic specimen can be placed in such a way that the soil is in contact with one or both sides of the specimen. The specimen is sheared at a rate selected by the user, but a maximum rate of 5 mm/min (0.2"/min) for geosynthetic/geosynthetic tests and 1 mm/min (0.04"/min) for soil/geosynthetic tests is currently recommended. The shear load is measured and plotted as a function of displacement, until a constant shear force is observed (usually deformations of 25 to 75 mm [1 to 3"] are required). The specimen is carefully examined to determine the location and mode(s) of shear failure. The peak shear stress recorded is plotted against normal compressive stress for at least 3 different normal stresses. The slope of the line formed by connecting the data points is the coefficient of friction of the specimen tested. The y-intercept of the plot is the adhesion of the specimen tested.

TEST EQUIPMENT:

Large scale direct shear apparatus, loading and recording devices. This standard is in the early stages of development at this time, so no standard equipment has been identified. Equipment is currently custom fabricated.

PERFORMANCE PROPERTY: PUNCTURE STRENGTH (CBR PLUNGER)
REFERENCED TEST METHOD: MODIFIED DIN 54307
ALTERNATIVE METHODS: DREXEL UNIVERSITY GRI #GS1-86
SCOPE: GEOSYNTHETICS
TARGET VALUE: PUNCTURE RESISTANCE
UNITS: N (lbf)

SUMMARY OF METHOD:

The referenced test method is a modified CBR plunger test using the test appparatus described in the German DIN standard. The test is performed in a CBR mold (inner diameter 150 mm [6"]) that is modified to hold a geosynthetic specimen. The plunger is a flat-tipped cylinder with a diameter of 50 mm (2") which moves at a rate of 60 mm/min (2.5"/min) until the specimen is ruptured. A force-deflection curve is plotted during testing. From this information, a load-deformation plot for the specimen is plotted.

Since the CBR apparatus is commonly used in geotechnical engineering, this procedure can easily be modified to generate design oriented performance data. Since the puncture resistance of a geosynthetic specimen may be very different when tested against soil as opposed to in the unsupported condition (as in the index test) the addition of soil to the CBR mold is a possibility. The soil can be compacted to a known density at a known moisture content and tested in a saturated condition. the test conditions may be selected by the user to model particular field conditions. The load-deformation behavior of the geosynthetic/soil system may be compared (with great care) to the soil tested alone. For special studies, the geosynthetic specimen can be overlain by another geosynthetic, a layer of soil or other material. The standard plunger can be replaced by another plunger designed to simulate gravel, crushed stone, shot rock, etc.

TEST EQUIPMENT:

Constant-Rate-of-Extension (CRE) testing device, modified CBR mold and plunger.

PERFORMANCE PROPERTY: IN-PLANE FLOW
REFERENCED TEST METHOD: ASTM 4617
ALTERNATIVE METHODS: SEVERAL EUROPEAN
SCOPE: GEOTEXTILES, GEONETS, GEOGRIDS, GEOCOMPOSITES
TARGET VALUE: HYDRAULIC TRANSMISSIVITY
UNITS: m^3/sec-m (gpm/ft)

SUMMARY OF METHOD:

Hydraulic transmissivity is determined by measuring the quantity of water which pass through the specimen in a specific time interval under particular conditions selected by the user. A specimen width of 300 mm (12") with an aspect ratio of at least 1 is suggested. Hydraulic gradients and normal compressive stresses selected for testing are site or application specific for this constant head method. For acceptance testing or general use, gradients ranging from 0.1 to 1.0 and compressive stresses from 25 to 250 kPa (500 to 5000 psf) are given as guidelines. Minimum seating periods of 15 minutes are suggested, although the need for longer periods is addressed. The use of site specific sub and superstrata, such as rigid plates, other geosynthetics or soil, is recommended.

Transmissivity for each test is reported as an average flow rate per unit width per unit gradient for the conditions examined. All values are corrected for temperature. Results are presented as plots of hydraulic transmissivity versus normal compressive stress, or hydraulic transmissivity versus time for constant stress levels.

TEST EQUIPMENT:

Equipment must be custom fabricated. No details are available at this time.

PERFORMANCE PROPERTY: WATER PERMEABILITY UNDER STRESS
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ---
SCOPE: GEOTEXTILES
TARGET VALUE: PERMITTIVITY
UNITS: sec^{-1}

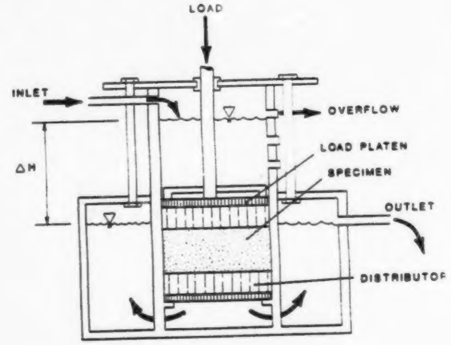
SUMMARY OF METHOD:

This method covers the determination of the water permeability of a single or multiple geotextile specimen under a normal compressive stress by the permittivity method. Because of the compressibility of the specimens, the permittivity, not permeability, is measured directly. The method can be used as an index test or as a design test in limited applications. It is intended to measure the effect of normal compressive stress on the permittivity of a geotextile specimen.

The test apparatus is a modified version of the one detailed in ASTM D4491. A piston applies a normal force to distributor plates overlying the geotextile specimen(s). The specimen thickness can be monitored during testing. The hydraulic gradient across the specimen is measured using manometers. Deaired water is recommended for testing. The test is performed using an initial normal compressive stress of 2kPa (0.29 psi), and additional stresses selected by the user are applied. The seating period for each applied stress is selected by the user. The rate of flow measurements and the permittivity calculations are performed as indicated in the draft procedure, and are identical to those presented in ASTM D4491. The permittivity under load reported is the average for at least five specimens.

TEST EQUIPMENT:

Modified permittivity device (see ASTM D4491), water deairing system. Details of permittivity apparatus will be provided with the completed test method when published.



PERFORMANCE PROPERTY: CLOGGING POTENTIAL
REFERENCED TEST METHOD: GRADIENT RATIO METHOD (Proposed ASTM)
ALTERNATIVE METHODS: LONG-TERM FLOW TESTS
SCOPE: GEOTEXTILES
TARGET VALUE: GRADIENT RATIO
UNITS: DIMENSIONLESS

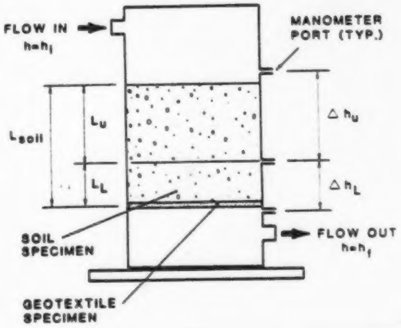
SUMMARY OF METHOD:

A circular geotextile specimen (111 mm or 4-3/8" diameter) is placed within a clear plastic permeameter over an open mesh support ring. About 1000 grams of dry soil, selected by the user, is placed loosely to a depth of 75 mm (3") over the geotextile specimen. The permeameter is assembled and all manometer ports (see figure) are attached. The soil/geotextile specimen is slowly saturated and then purged of oxygen with carbon dioxide to reduce the occurrence of air bubbles. In addition, it is recommended that the test be run using deaired water at room temperature.

Successive hydraulic gradients of 1.0, 2.5, 5.0, 7.5 and 10.0 are placed on the specimen for 24 hours each. Additional hydraulic gradients or testing times can be applied if required. The system flow rate and static head at several levels within the soil/geotextile specimen are monitored. The gradient ratio for each set of manometer readings is calculated. The gradient ratio is defined as the ratio of the head loss across the downstream 1" of the test soil and the geotextile to the head loss across the upstream 50 mm (2") of the test soil. The gradient ratio values are a function of the geotextiles, soil and test conditions. The relationship between test results and actual field conditions has not been established. The reproducibility of test results using a "standard" soil is being investigated by an ASTM D-35 Task Group. The test device is also suitable for long-term soil/geotextile permeability tests.

TEST EQUIPMENT:

Permeameter-drawings will be available from ASTM. Water deairing system (recommended).



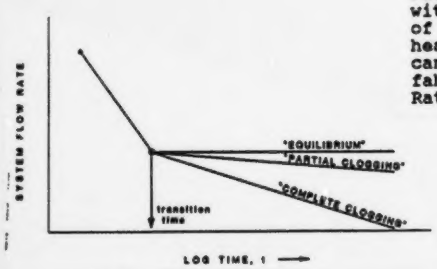
PERFORMANCE PROPERTY: LONG TERM CLOGGING POTENTIAL
REFERENCED TEST METHOD: DREXEL UNIVERSITY GRI #GS 1-86
ALTERNATIVE METHODS: ---
SCOPE: GEOTEXTILES
TARGET VALUE: LONG TERM FLOW RATE
UNITS: Liters/day (gal/day)

SUMMARY OF METHOD:

The referenced test method covers the evaluation of the long term flow rate of a soil/geotextile system. The trend of the long term flow rate provides an indicator of the clogging potential of the system.

The test is essentially a constant head test using specially build apparatus. Testing devices used for the Gradient Ratio or permittivity under stress tests can also be used. The pre-conditioned specimen is placed in the device and 150 mm (6") of the test soil is placed over the specimen. Undisturbed or remolded soils can be used, although there are some limitations on soil compaction. Anti-seep collars are used to reduce the development of preferential flow paths along the outer perimeter of the soil sample. Water is then introduced and maintained at a constant head selected by the user. The flow data is recorded immediately to establish the initial portion of the curve. A detergent or bleach (such as Chlorox) must be added to the test water on a daily basis to eliminate bacteria growth within the specimen.

The flow rate will initially decrease with time due to densification of the soil. At some time, the flow rate will appear to stabilize. This transition time is dependent on the type of soil used and the initial soil density. The slope of the flow rate versus time line for data recorded after the transition time provides an indication of clogging potential of the system. Three long term conditions are described in the test procedure: Equilibrium, Partial Clogging, and Complete Clogging. These conditions are illustrated on the figure below which is a plot of the system flow rate versus log of time. Several tests run concurrently can provide a direct comparison of several candidate geotextiles using the same soil, or a single geotextile may be tested with serveral different soils.



TEST EQUIPMENT:

Flanged plexiglass column with specimen support capable of maintaining a constant head on the specimen. Device can easily be custom fabricated, or a Gradient Ratio device can be used.

PERFORMANCE PROPERTY: TENSILE CREEP
REFERENCED TEST METHOD: PROPOSED ASTM
ALTERNATIVE METHODS: ---
SCOPE: GEOSYNTHETICS
TARGET VALUE: TIME TO FAILURE OR TOTAL STRAIN
UNITS: Hours or %

SUMMARY OF METHOD:

Synthetic polymers used in geosynthetics are prone to creep, or increased elongation with time for a constant tensile load. The geosynthetic can ultimately rupture at loads significantly less than the breaking strength recorded using other methods.

The proposed ASTM procedure is in its initial draft stage at this time; therefore, details of the test will not be discussed. A general creep testing procedure is presented. For an overview of creep testing procedures and terminology for testing of plastics, a review of ASTM D2990 is recommended.

The breaking load of the geosynthetic is determined by a standard tensile test, ASTM D4595 (Wide Strip Method), is recommended. An identical set of specimens are loaded in tension by a system of dead weights at load levels of a known percentage of the ultimate breaking load. The load levels and other test conditions (such as temperature) are selected by the user to best model anticipated field conditions. The elongation of the specimens are monitored under the sustained tensile load. The strain or strain rate is recorded and plotted against the log of test time. The testing time is generally user and application specific. From a family of creep curves, the creep behavior may be extrapolated for the life of the application, or a safe load level (i.e., one where excessive creep of the specimen is not observed over the time tested) is selected for design. Caution is advised in interpreting time-dependent visco-plastic behavior of geosynthetics (creep or stress relaxation) since this behavior is dependent on many factors and is difficult to extrapolate in plastics.

TEST EQUIPMENT:

Creep frame, loading system, elongation monitoring equipment, suitable clamps, and a Constant-Rate-of-Extension (CRE) tensile testing device for determination of the geosynthetic breaking load.

PERFORMANCE PROPERTY: COMPRESSIVE CREEP
REFERENCED TEST METHOD: DREXEL UNIVERSITY GRI #GS 4-87
ALTERNATIVE METHODS: ---
SCOPE: ALL GEOSYNTHETICS
TARGET VALUE: TIME DEPENDENT THICKNESS UNDER STRESS
UNITS: mm - hr (inches - hr)

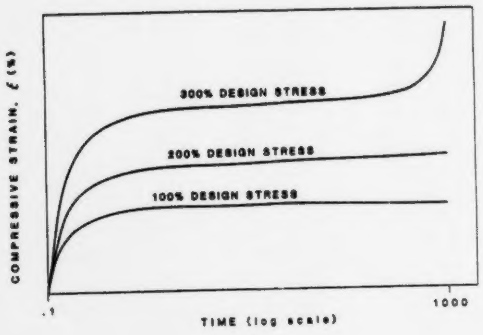
SUMMARY OF METHOD:

The referenced test method covers the determination of the compressive creep of geosynthetics, especially geocomposites, geonets and geotextiles. The time-dependent specimen thickness is recorded for a constant compressive stress, or a series of compressive stresses. For index testing, seating periods of 100 hours and load levels of 20, 40 and 60% of the specimen breakdown or crush strength are suggested. For design testing, seating periods of 1000 hrs and load levels of 100, 200 and 300% of design stresses are selected. Site specific fluid or elevated temperatures may be used in testing.

Geosynthetic specimens, measuring at least 150 mm (6 in) square are placed between two rigid platens in a device similar to a soil consolidometer. The deformation of the specimen under constant normal stress, selected by the user, is recorded. At the end of the seating period, the next (greater) stress level is applied and the deformation is recorded. For multiple stress levels, a family of creep curves is generated, as shown in the figure below. The strain rate may be calcualted for use in creep prediction models.

TEST EQUIPMENT:

Device capable of applying and maintaining a constant normal compressive stress to the specimen, and dial gauge or LVDT to measure deformation. Modified soil consolidometers, which are commercially available, are satisfactory for most geosynthetics.



PERFORMANCE PROPERTY: FLOW CHANNEL INTRUSION
REFERENCED TEST METHOD: DREXEL UNIVERSITY GRI #GS 5-87
ALTERNATIVE METHODS: ---
SCOPE: GEONETS AND GEOCOMPOSITES
TARGET VALUE: REDUCTION IN OPENING AREA
UNITS: %

SUMMARY OF METHOD:

The above refereced method covers the determination of the degree of intrusion of an adjacent geotextile or geomembrane into the openings of a geonet or geocomposite. The goal is to measure the decrease in cross-sectional open area available for planar flow of fluids. On-site soil or other surfaces can be used to model field conditions. At this time, no prediction regarding the reduction of planar flow capacity of the specimen is made. The mechanisms of intrusion and core or net deformation may be visually identified.

The normal compressive stress and seating period are selected by the designer to best model field conditions. Specimens are 150 mm (6") square and are caulked around their perimeter with a flexible silicon caulk. A soil substrate, if desired, is placed on the rigid base of the test device and the geosynthetic specimen is placed over it. Two rigid tubes are placed within the geonet or core to serve as the inlet and outlet for an epoxy resin. The soil superstratum is placed over the specimen. The normal compressive stress is applied for a period of at least 15 minutes. A quick setting epoxy is then injected into the specimen until the specimen is completely inpregnated. The resin is allowed to set under the constant compressive stress for at least 24 hours. The specimen is removed from the holder and sectioned for observation. Photographs of the sections may be taken and the reduction in void area may be calculated.

TEST EQUIPMENT:

Testing device capable of applying and maintaining normal compressive loads up to 50 kN (10,000 lbf), steel specimen holder and eopxy resin injection equipment.

PERFORMANCE PROPERTY: GEOCOMPOSITE BOND STRENGTH
REFERENCED TEST METHOD: ASTM F904
ALTERNATIVE METHODS: ---
SCOPE: GEOCOMPOSITES
TARGET VALUE: FORCE TO SEPARATE PLIES
UNITS: gm/25 mm (lbf/in)

SUMMARY OF METHOD:

The referenced test method was developed to compare bond strength or ply adhesion of similar laminates from such materials as paper, plastic film and foil. This test method has been used to determine the ply adhesion of geotextiles to geonets or drainage cores. Although a peel adhesion load is recorded, this method is not recommended for determining the performance of a geocomposite in cases where the bond could fail in shear (such as for geocomposites placed on the sidewalls of a waste cell).

Five specimens are cut to a width of 25 mm (1 in.) and a length of 250 mm (10 in.) Specimens are tested in the machine and cross-machine direction. Separation of the plies is initiated by the user manually or by the use of a softening solvent. The specimens are clamped and pulled at a rate of 280 mm/min (11 in/min). The force required to separate the first inch is ignored and the average force to separate the following 2 inches of bond is determined. The average force is expressed in gm/25 mm (lbf/in).

TEST EQUIPMENT

Constant-Rate-of-Extension (CRE) Tensile Testing Device, grips.

INDEX

Allowable Leachate Head III-4
Alkalinity III-8
Anchorage III-21,V-3,VI-13
Apparent Opening Size(AOS) III-7
Arrhenius Model VII-1
Asthetics VII-20
Bedding Layer I-10
Berms IV-4
Biaxial Tension V-19
Biological Growth I-4,10,V-13, VII-3,13
Biotic Barrier V-12
Chemical Attack VII-1,10
Clogging III-8,VI-26
Coefficient of Uniformity III-7
Composite Liner I-6
Compressive Creep III-5
Concrete VI-15
Construction FML:VI-8, LCR:VI-28
Cover System I-8,V-1
CPE(Chlorinated Polyethylene) I-2, III-19,20,V-10
Creep(Relaxation) VII-10
CSPE(Chlorosulfonated Polyethylene) I-2,VI-5,12
Darcy's Equation I-1,III-2,11
Design Ratio II-1,III-6,25
De Minimis I-6,7,III-10,12,V-8
Direct Shear Test III-9
Downdrag IV-5,6
Drainage Layer I-10,III-3
Environmental Stress Cracking VI-4,VII-6
Environmental Stress Rupture VII-7
Extrusion Weld VI-12
Fabrication VI-6
Fick's Law III-11
Filter I-10,III-7,8,V-6
Fine-Finish of Subgrade VI-30
Freeze-Thaw III-25,IV-2,V-3
Gas III-27,V-3,12,15
Geocomposites I-4
Geomembrane I-1
Geonets I-4
Geotextiles I-4
Gradient Ratio Test III-8
HDPE(High Density Polyethylene) I-2,III-14,16,18,IV-6,V-10,16, VI-3,5,8,11,VII-9
HSWA I-1,5,10
Hydrolysis VII-15
Impact Test III-20
Index Tests II-1
In-plane Flow II-1
Installation FML:VI-15, LCR:VI-27
Leachate III-2
Liquids Management I-8
Manpower VI-8
Melt Index VI-3
Monitor(LCR) IV-8 to 11
MTG(Minimium Technology Guidance) I-5,8,III-1,2,3,8,10,V-1,8,15
NDT VI-5
NSF 54 I-2
Ozone VII-2
Panels VI-7,9,22
Peel Test III-16
Percolation Velocity III-4
Performance Tests II-1
Permittivitty VII-11
Post Closure I-6
PVC(Polyvinyl chloride) I-2,V-10, 16,VI-5,VII-9,13
Puncture Test III-17
Quality Assurance VI-1,17,21,31
Quality Control VI-1,17,21
Ramp IV-1
RCRA I-5,8,9,V-1,3,5
Resin VI-3
Roadway IV-1
Rodents V-8,12,VII-19
Roots V-8,V-12,VII-17
Sample Size VI-20
Sampling Strategies VI-19,27
Scrim III-10
Seams III-10,15,V-10,VI-2,6,11,12
Seam Repair VI-24
Sealing VI-2,15
Secondary Containment III-1
Secure Landfill I-5
Settlement III-9,13,V-3,7,9
Shear Test III-16
SIAR(Surface Impoundment Assesment Report) I-9
Soil Cover III-26
Soil Burial VII-8,15
Specifications FML:VI-12, LCR:VI-25
Standpipe IV-5,8
Sterilization of Soil VI-29

Surface Impoundment I-9
SWCR(Surface Water Collection/
    Removal) V-5
Survivability III-19,V-11
Tear Test III-17
Thermal III-15,VI-10,VII-5,14
Thermoplastic I-2
Topsoil V-2
TGD(Technical Guidance Document)
    VI-1,25
Transmissivity III-2,3,5,27,V-5,15
    VI-26
UV(Ultraviolet)Aging I-2,III-19,
    20,V-10,VII-2
Ultrasonic Side Shadow VI-5
Uplift VI-13
Vegetation V-1
Vent Pipe V-16
Wind III-25,V-1,VI-5,10,13,VII-17,
    19
WVT(Water Vapor Transmission)
    III-11,V-8